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Powerful new telescopes will open the next frontier
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FUTURE OF REPRODUCTION
Could skin cells replace sperm and eggs?
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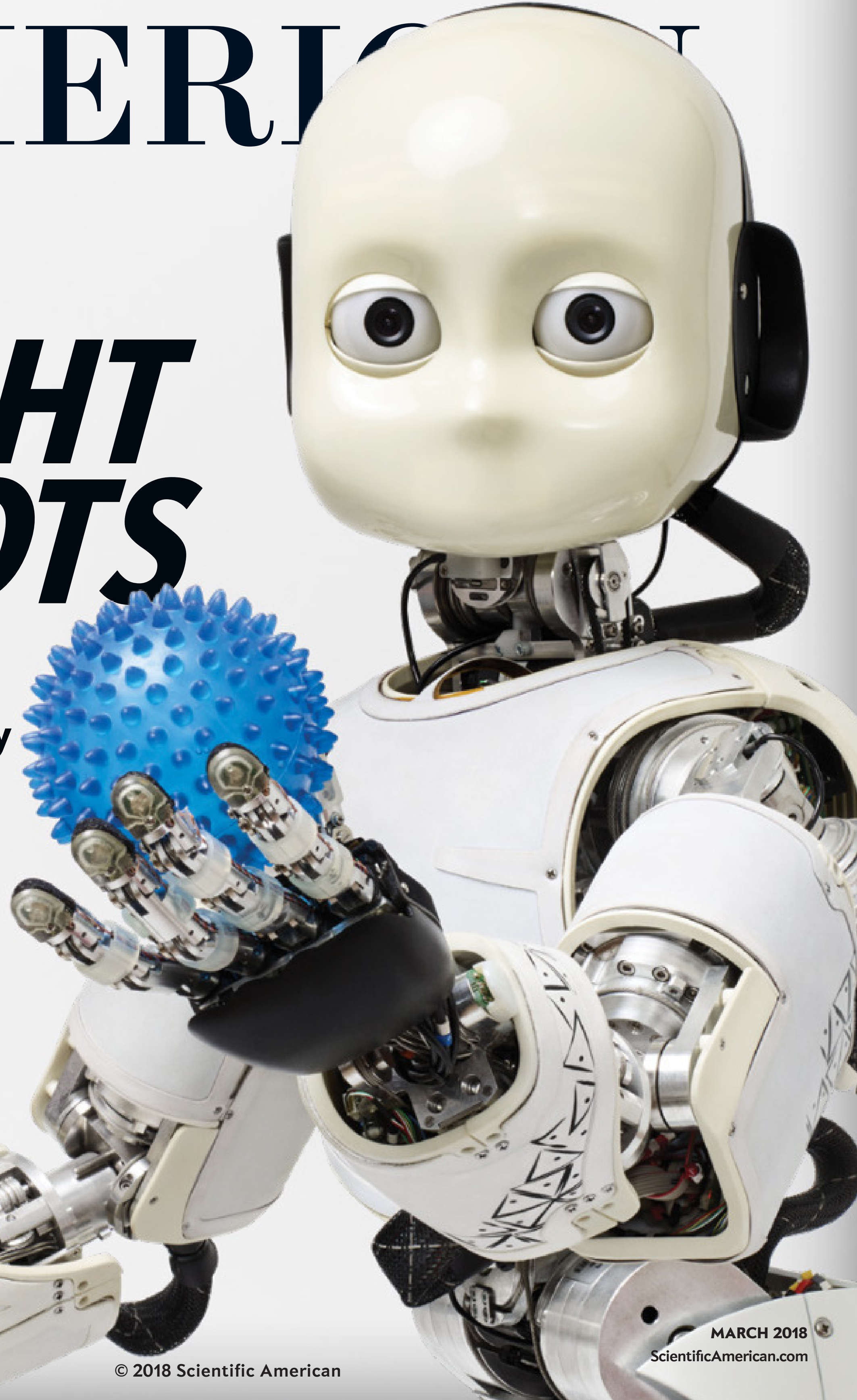
SELF-TAUGHT ROBOTS

Artificially intelligent machines are starting to learn spontaneously



PLUS

BUILDING A BACKUP BEE

Replacing the embattled honeybee
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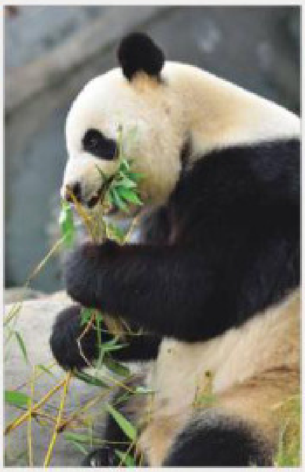

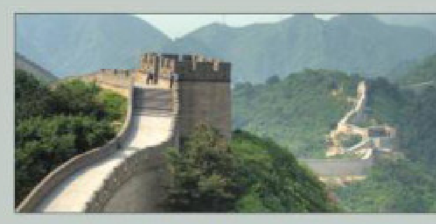

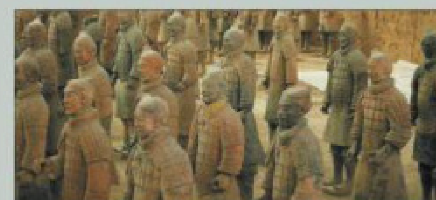

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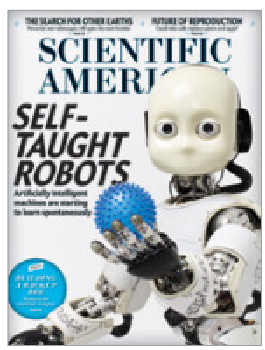

ON THE COVER
ICub, an android being studied at the University of Plymouth in England, can learn like a child by experimenting with its body and with objects in its environment. Such robots are helping researchers explore new avenues in machine intelligence while yielding insights into child development. Photograph by Sun Lee.

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ON THE WEB

"Fake" Transparency
Scientific American investigates how government agencies subtly control the flow of scientific information to the press, even as their media policies preach transparency.
Go to www.ScientificAmerican.com/mar2018/gov-info

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Mariette DiChristina is editor in chief of *Scientific American*. Follow her on Twitter @mdichristina

Child's Play

Once they "understand" a topic or game completely, computers can calculate solutions with stunning speed, far faster than the wetware in our skulls. AlphaGo Zero, from British company DeepMind, accumulated experience by competing against itself millions of times to master the game Go and now exceeds the skills of the game's human experts. That's a remarkable achievement over the first version, AlphaGo, which had mined the data from numerous games played by people. But it was a limited accomplishment nonetheless, given that even the ancient game of Go has clear, finite rules.

Babies, in contrast, rapidly adapt and learn how to manage in surroundings that are continuously changing and where the criteria for success in any endeavor (even for adults) are hardly ever clear. Their brains make predictions about what will happen in a situation, from patting a puppy to fitting a piece in a jigsaw puzzle. Then they experiment with their bodies and with objects, observing and analyzing the world around them. Millions of years of evolution have led to a superior learning system—one that today's roboticists hope to deploy to improve machines controlled by AI, or artificial intelligence. In our cover story, "Self-Taught Robots," journalist Diana Kwon explores how programming algorithms to learn like children is both transforming robotics and providing some insights into child development. Turn to page 26 to see what robotic "children" are teaching us adults.

It's common to think of backup files for your laptop, but how about for pollinators? In "Building a Backup Bee," starting on page 66, author Paige Embry writes about how the world's largest almond grower is developing a replacement for honeybees called the blue orchard bee, or BOB. Honeybees have experienced devastating losses in recent years, having been victims of pests, disease, poor nutrition, pesticide exposure and the stresses of literally being trucked around to service different crops as they bloom. Unlike social honeybees, BOBs are solitary—and amazingly efficient. Assuming the challenges of making these insects into managed pollinators can be surmounted, a few hundred BOBs can do the work of 10,000 honeybees.

Further adventures at the frontiers of science await: Read "The Baddest Bite," by Gregory M. Erickson (*page 40*), for the secrets of the crocodiles and their relatives' evolutionary success. John Gabrieli (*page 54*) provides "A Look Within" at imaging technologies that could find the best treatments for depression and addiction in our brains. "Island of Heavyweights," by Christoph E. Düllmann and Michael Block (*page 46*), describes the race to find the world's heaviest elements—and the "island of stability" in chemistry, where novel elements could last for minutes or even years. We hope you enjoy the journey. SA

Illustration by Nick Higgins

November 2017

CONSCIOUS POINT

Christof Koch's article on "How to Make a Consciousness Meter" discusses a technique purporting to deduce whether severely brain-injured patients are conscious by sending magnetic pulses to the brain while measuring its electrical activity and then creating a mathematical measure of the response called the perturbational complexity index (PCI).

This article is problematic on several levels. Koch interprets the PCI data in one study as showing that some unresponsive brain-damaged patients have something akin to consciousness because they have a PCI value above a threshold that the researchers had established for conscious subjects. But that range includes the state of REM sleep, which he defines as "Unresponsive, Conscious" in the "Zapping and Zipping" box. If consciousness is "the quality or state of being aware," as per Merriam-Webster, then to equate any neural activity with consciousness would require evidence that the activity was a response to a sensory input. Only if data emerge demonstrating that these patients have a prognosis that is less dismal than for other persistently unresponsive patients should the PCI be used as a possibly hopeful sign for physicians and families.

Further, Koch blatantly misstates the nature of Terri Schiavo's death: he calls it "medically induced," when, in fact, Schiavo was kept alive for years with medical intervention and died when it was stopped and her body was allowed to follow the natural course of severe brain damage. Her death was delayed by medical treatment, not caused by it.

"Terri Schiavo's death was delayed by medical treatment, not caused by it."

DAVID HERBERT *SUTTER INDEPENDENT PHYSICIANS, SACRAMENTO*

David Herbert
Sutter Independent Physicians, Sacramento

Koch's article focuses on the cutoff for consciousness, but what about the spread of the PCI? Might the value slide as one is ravaged by Alzheimer's disease? Does it correlate with age or IQ in healthy individuals? Baby steps come first, but I am excited at the prospect that the PCI might elucidate the connection between consciousness and the physical structure of the brain.

Mark G. Kuzyk
Regents Professor of Physics, Washington State University

TARGET BEST PRACTICE

"Health by the Numbers?" by Claudia Wallis [The Science of Health], argues that individuals should have personalized goals for levels of, say, glucose and cholesterol rather than one-size-fits-all targets, which certainly makes sense to me.

The article says that for decades doctors have told patients who are prediabetic or who have diabetes to aim for a blood level of hemoglobin A_{1C} below 7 percent. Actually, while many doctors do try to control A_{1C} below that level, not all of them follow that criterion. Rather if the A_{1C} is found to be above the prediabetes threshold of 5.7 percent, they start prescribing medication, often metformin. I know friends who have been put on metformin with levels of around 6.1 percent.

I wonder how many patients are being overtreated by adherence to the 5.7 percent criterion. I do understand the need to be proactive in preventing diabetes, and there may be other medical factors that might call for tight control. As pointed out in the article, however, there are possible negative consequences of overtreatment (comprehensively studied in a 2016 paper by René Rodríguez-Gutiérrez and Victor M. Montori, both at the Mayo Clinic).

Jack Holtzman *San Diego*

Wallis references a published risk-estimation tool for heart attacks and stroke that factors in cholesterol levels. My online searches have produced other references to the tool but no links. Is it available to the public?

Robert Grane *via e-mail*

WALLIS REPLIES: Regarding Holtzman's letter: Although doctors will sometimes prescribe metformin for patients with prediabetic A_{1C} levels (between 5.7 and 6.4), a report by Eva Tseng of Johns Hopkins University and her colleagues published last year in Diabetes Care *indicates that fewer than 1 percent of people with prediabetes take metformin. Typically the first-line treatment for such patients is exercise, weight loss and modification of diet. That said, metformin is believed to be safe and effective for both prediabetes and type 2 diabetes and does not cause hypoglycemia or other risks associated with some diabetes drugs.*

In answer to Grane: You can find a risk estimator from the American College of Cardiology online at http://tools.acc.org/ASCVD-Risk-Estimator-Plus/#!/calculate/estimate

OPIOIDS AND POLICY

Thanks to Carl L. Hart for his insightful article "People Are Not Dying Because of Opioids" [Forum], which suggests reasoned public health approaches to address addiction and overdose that won't harm patients in need.

My husband and I are physicians. We are also disabled because of painful conditions that are expected to worsen until death. Like so many others, thanks to misinformation about the "opioid epidemic" and misguided efforts to do something about it, we have lost access to care more than once. Patients are dying from complications of untreated pain and committing suicide. Where you live determines wheth-

er you will be overprescribed or underprescribed pain medicine, but many physicians are now refusing to prescribe at all. Hart's article was a breath of fresh air.

NAME WITHHELD *via e-mail*

ADDING SPACE

"The Zoomable Universe," an excerpt of a book by Caleb Scharf and Ron Miller, invites simultaneous consideration of the age *and* size of the knowable universe. It estimates the diameter of the universe to be 93 billion light-years. If the speed of light is a limiting factor and the universe is approximately 13.8 billion years old, how can the radius of the universe be more than 13.8 billion light-years and thus the diameter be greater than approximately 27.6 billion light-years?

JOHN C. MASTERS *Sarasota, Fla.*

THE EDITORS REPLY: Current estimates place the radius of the observable universe as just more than 45 billion light-years, yielding a diameter slightly in excess of 90 billion light-years. The reason this value is larger than 27.6 billion is because of the universe's expansion over the course of its 13.8-billion-year existence. While it's true that nothing can travel faster than light through space, the expansion of space itself can exceed this cosmic speed limit.

WELL VERSED

"The Radical Groundwater Storage Test," by Erica Gies, proposes several methods of recharging underground aquifers in California, including the controlled flooding of farm fields adjacent to rivers and streams. Such flooding may help refill the aquifers, but it can be troublesome. When a government official persuaded my family to flood our ranch in Santa Barbara County sometime in the 1950s, it resulted in severe erosion, and we never did it again. A more efficient method is to pump the water down wells drilled into the aquifer that needs to be recharged. These could even be the same wells that are used to pump water out for use during the growing season. And injecting directly into the aquifer mitigates the risk of transporting pesticides and fertilizers and may result in a more rapid fill rate.

JOSEPH A. RUSSELL *via e-mail*

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Science Suffers from Harassment

A leading organization has said that sexual harassment is scientific misconduct. Where are the others?

By the Editors

Last fall, as the horrific allegations of sexual misconduct and assault against entertainment titan Harvey Weinstein started to emerge, details of another alleged case came to light, not from a Hollywood casting couch but from remote scientific research stations in Antarctica. Two former graduate students of prominent Boston University geologist David Marchant lodged formal complaints against their onetime mentor, saying that he had sexually harassed them during research expeditions nearly 20 years ago. One complainant alleged that Marchant called her a "slut" and a "whore," threw rocks at her when she went to the bathroom in the field and goaded her to have sex with his brother, who was also on the expedition. After a 13-month investigation, the university concluded that Marchant had indeed engaged in sexual harassment. Marchant has appealed the finding.

The case is one in a string of allegations leveled against high-profile scientists in recent years that add to a growing body of evidence that science, like Hollywood, is rotten with sexual misconduct. In a survey published in 2014, 71 percent of female respondents said they had been sexually harassed during field research, and 26 percent said they had been sexually assaulted. In a follow-up study, survey participants described psychological trauma from the encounters that compromised their ability to continue their research. Some abandoned their careers altogether.

Science, like all human endeavors, benefits from diversity. Yet women hold just 24 percent of jobs in science, technology, engineering and medicine. If factors such as sexual misconduct are driving women out of science, then the scientific community must act. To that end, last September the nearly 60,000-member American Geophysical Union (AGU) took the bold step of revising its ethics policy to treat harassment (including sexual harassment), discrimination and bullying as scientific misconduct, with the same types of penalties for offenders. Other scientific organizations have not adopted that standard, and we think they should.

Allegations of sexual misconduct have long played out in parallel justice systems because criminal justice in practice is so ineffective. In academia, victims of sexual harassment and assault typically funnel their complaints through Title IX, a law that forbids sex-based discrimination, including sexual harassment and sexual violence, in colleges and universities that receive federal funding.

But some critics complain that the Title IX system is deeply flawed, allowing institutions with a vested interest in protecting their reputations to play the roles of detective, judge and jury. In October 2017 *Scientific American* reported that many sexual misconduct victims feel let down by inaction by their institutions.

A number of scientific societies have recently issued statements condemning sexual harassment and assault, along with guidelines for ethical behavior among their members. The AGU's approach is stronger and more direct. It argues that harassment is as egregious as the big scientific sins of data fabrication, falsification and plagiarism. Members found guilty of sexual harassment may thus be banned from presenting at conferences or publishing their research in AGU-run scientific journals, among other consequences that would limit their participation in the field.

Some argue that research should stand on its own merit, regardless of the personal behavior of the scientists themselves. But "science is not being done outside of interpersonal interactions," says anthropologist Robin Nelson of Santa Clara University, a coauthor on the two recent studies that looked at harassment in the field. Behavior that silences other voices subverts the entire scientific enterprise. If that's not misconduct, we don't know what is.

The AGU's policy will not solve the problem alone. Scientific societies have limited means and authority to investigate and adjudicate and thus rely mainly on the home institutions of perpetrators to handle allegations of sexual misconduct. Nicholas Steneck, a research integrity consultant and emeritus professor at the University of Michigan, notes that a change in the federal definition of research misconduct to include sexual misconduct, though unlikely, would have a far greater impact because it would have legal standing with agencies and research institutions.

But classifying harassment as scientific misconduct sends a powerful message about its destructive effects on victims and on scientific progress as a whole—and will help pave the way to creating a culture where discovery and innovation can flourish. SA

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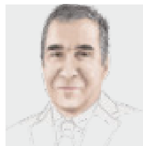
Illustration by Alice Yu Deng



Andrew A. Rosenberg is director of the Center for Science and Democracy at the Union of Concerned Scientists.

Time for a Reboot in Congress

The antiscience chair of the science, space and technology panel is leaving

By Andrew A. Rosenberg

Republican Representative Lamar Smith of Texas will retire from Congress in 2018. Smith has run the powerful House of Representatives Committee on Science, Space, and Technology since 2013. Unfortunately, he did not use his position to seriously advance science policy but instead wielded it as a cudgel against perceived political enemies—including scientists. He sponsored legislation championed by lobbyists and trade groups that would, had it become law, have undermined the role of science in policy making. And he stood shoulder to shoulder with Environmental Protection Agency administrator Scott Pruitt as they gutted the independence of that agency's science advisory panels. Smith went after individual scientists, science programs and even science grants as part of his "oversight" efforts, all in an apparent attempt to stifle both the process and the outcomes of scientific work whose results might offend his allies in polluting industries.

In 2015 the House gave Smith the unusual ability to issue subpoenas unilaterally, without the input of the minority party. He used it to subpoena e-mails and documents from scientists at the National Oceanic and Atmospheric Administration over a peer-reviewed climate study they published in the journal *Science.* In issuing these subpoenas, Smith contended, without evidence, that the scientists altered data about climate change. A congressional subpoena is an intimidating tool, and the American Meteorological Society wrote to the committee to protest this use of subpoena power. In 2016 my own organization, the Union of Concerned Scientists (UCS), was hit with a subpoena from the House science committee demanding its correspondence with state attorneys general. The UCS rejected the request, and Smith's staff declined our offer to brief the committee.

With a new chair comes a great opportunity to deal with the real challenges confronting our scientific enterprise. How can we continue to maintain world leadership across a multitude of fields and at the same time deepen and support international partnerships? How can we strengthen our training and early career prospects for scientists in both well-established and emerging fields of study? What effective new approaches should we adopt to train the technically proficient workforce the economy needs? How can we tackle long-standing disparities in our science and technology workforce arising from individuals' income, race, gender and other factors? How can our federal scientific workforce be strengthened? How can scientific integrity be fully implemented in federal agencies? And how can we best put science to work to advance public health and environmental justice? These are just a few of the substantive and challenging issues a functional science committee would address.

Oversight should focus on the structure, function and outcomes of agency actions with regard to legal mandates. There must be hearings on the recent change in science advisory boards, for example, as well as scientific integrity policies across the government (26 agencies have such policies, which are intended to protect against political interference in science). We need congressional oversight to make sure political appointees are implementing and abiding by these policies.

The science community and all those who care about science-based policy making should speak out for a new direction for the House science committee now that the dark period of Smith's chairmanship is coming to a close. As one former Republican chair of the committee, Sherwood Boehlert, wrote in a 2010 opinion piece for the *Washington Post,* "no member of any party should look the other way when the basic operating parameters of scientific inquiry ... are exploited for the sake of political expediency. My fellow Republicans should understand that wholesale, ideologically based or special-interest-driven rejection of science is bad policy. And that in the long run, it's also bad politics." SA

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Illustration by Christian Dellavedova

ADVANCES

The earliest Proto-Indo-European speakers were likely nomadic horse riders.

LINGUISTICS

Mother Tongue

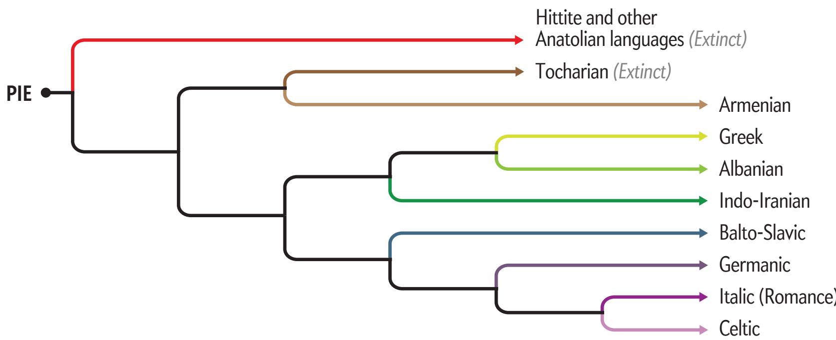
Genetic evidence fuels debate over a root language's origins

Five thousand years ago nomadic horseback riders from the Ukrainian steppe charged through Europe and parts of Asia. They brought with them a language that is the root of many of those spoken today—including English, Spanish, Hindi, Russian and Persian. That is the most widely accepted explanation for the origin of this ancient tongue, termed Proto-Indo-European (PIE). Recent genetic findings confirm this hypothesis but also raise questions about how the prehistoric language evolved and spread.

No written record of PIE exists, but linguists believe they have largely reconstructed it. Some words, including "water" (*wódr̥*), "father" (*p*H_2*-ter*) and "mother" (*me*H_2*-ter*), are still used today. Archaeologist Marija Gimbutas first proposed the Ukrainian origin, known as the kurgan hypothesis, in the 1950s. Gimbutas traced the language back to the Yamnaya people, herders from the southern grasslands of modern-day Ukraine who domesticated the horse.

In 2015 a series of studies sequenced the DNA of human bones and other remains from many parts of Europe and Asia. The data suggest that around 3500 B.C.—roughly the same time that many linguists place the origin of PIE and that archaeologists date horse domestication—Yamnaya genes replaced about 75 percent of the existing human gene pool in Europe. Together with the archaeological and linguistic evidence, the genetic data tipped the scales

Illustration by Chris Gash



A large number of languages spoken today—including English, Hindi and Persian—descended from a single root tongue, Proto-Indo-European. New genetic evidence supports the idea this language was spread by Ukrainian steppe nomads on horseback. This diagram is highly stylized and is meant to show only general relations among language groups, not actual dates of divergence.

heavily in favor of the kurgan hypothesis.

Newer findings complicate the story, however. In a study published last June in the *Journal of Human Genetics,* researchers sequenced the mitochondrial DNA of 12 Yamnaya individuals, along with their immediate predecessors and descendants. The remains were found in burial mounds, or kurgans (from which the theory takes its name), in modern-day Ukraine. They had been buried in layers atop one another from the end of the Stone Age through the Bronze Age, between about 4500 and 1500 B.C.—the same time as the genetic replacement event in Europe. The earliest and midrange specimens' mitochondrial DNA (which is inherited from the mother) was almost entirely local. But the mitochondrial DNA of the most recent specimens included DNA from central Europe, including present-day Poland, Germany and Sweden. This discovery indicates that "there were pendulum migrations back and forth," says lead author Alexey Nikitin, a professor of archaeology and genetics at Grand Valley State University. In other words, he adds, "it wasn't a one-way trip."

These findings give the kurgan hypothesis "a lot more credit," Nikitin says. But he contends that his new results also show the migration was on a smaller scale than previously speculated; the more recent specimens apparently only made it as far as central Europe before returning, even though the language eventually spread as far as the British Isles. Nikitin also believes the dissemination was not as violent as it is often made out to be. "A military campaign would explain the genetic replacement. But that's [unlikely to have been] the case," he says.

David Anthony, an anthropologist at Hartwick College, who co-authored several of the earlier genetic studies but was not involved in the latest work, calls the new findings very convincing. "The domestication of the horse created a steppe bridge into India and Iran on the one side and Europe on the other side," Anthony says. "When [the] Yamnaya people moved into eastern and western Europe, their genetic signature was very different from what was there before," he explains. "That's what makes it paint such a clear picture [of how the root language spread] and why you can really see the migrations so easily on a map."

Yet Anthony disagrees with the interpretation that this was a small and mostly peaceful affair. Without written words, language transmission at the time would have depended largely on face-to-face contact, he says, suggesting the PIE speakers swept well across Europe and Asia. He believes linguistic and archaeological evidence, including weapons found in graves, suggests the language's progenitors had a warrior culture. Nikitin argues the ax-heads were purely "decorative," however.

Both researchers caution against reading too much into genetic evidence alone. Many other social and cultural forces were at play. "Language shifts generally flow in the direction of groups that have higher economic status, more political power and higher prestige," Anthony says. "And in the most brutal situations, it will flow in the direction of people who survived."

—Roni Jacobson

SOURCE: "MAPPING THE ORIGINS AND EXPANSION OF THE INDO-EUROPEAN LANGUAGE FAMILY," BY REMCO BOUCKAERT ET AL., IN SCIENCE, VOL. 337; AUGUST 24, 2012

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GETTY IMAGES

NEUROSCIENCE

Brain Enigma

WWII code-breaking techniques help to translate neural signals

During World War II, cryptographers cracked Germany's Enigma code by exploiting known language patterns in the encrypted messages. Using the expected frequencies and distributions of certain letters and words helped British computer scientist Alan Turing and his colleagues find the key to translate gibberish into plain language. Now researchers are borrowing from the world of cryptography to convert brain signals into limb movements.

Many human motions, such as walking or reaching, follow predictable patterns. With this in mind, Eva Dyer, a neuroscientist at the Georgia Institute of Technology and Emory University, developed a cryptography-inspired strategy for neural decoding. She and her colleagues published their results last December in *Nature Biomedical Engineering.*

"I've heard of this approach before, but this is one of the first studies that's come out and been published," says Nicholas Hatsopoulos, a neuroscientist at the University of Chicago, who was not involved in the work. "It's pretty novel."

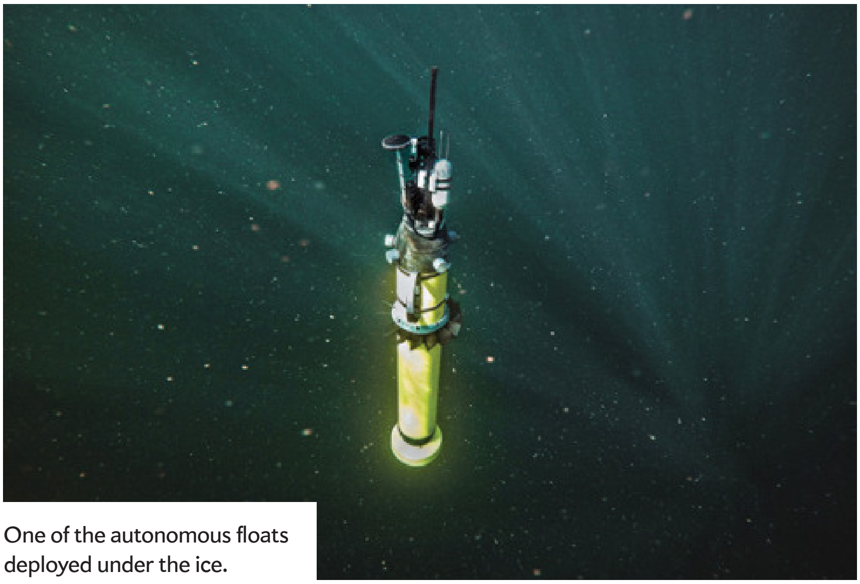
Existing brain-computer interfaces, such as those that control some prosthetic limbs, typically use algorithms called supervised decoders. These rely on simultaneous recording of both neural activity and moment-by-moment movement details, including limb position and speed—a time-consuming, laborious process. This information is then used to train the decoder to translate neural patterns into their corresponding movements. In cryptography terms, this would be like comparing a number of already decrypted messages with their encrypted versions to reverse engineer the key.

In contrast, Dyer's team sought to predict movements using only the "encrypted messages" (neural activity) and a general understanding of the patterns that pop up in certain movements. The scientists trained three macaques to use arm or wrist movements to guide a cursor to a number of targets on a screen. At the same time, implanted electrodes recorded signals from about 100 neurons in each monkey's motor cortex—a brain region that controls movement. The researchers then tested a slew of computational models to find the one that best mapped patterns buried in the neural activity onto patterns they had seen in the animals' movements.

When the researchers used their best model to decode neural activity from individual trials, they could predict the macaques' actual movements on those trials about as well as some basic supervised decoders. "It's a very cool result," says Jonathan Kao, a computational neuroscientist at the University of California, Los Angeles, who was not involved in the study.

Dyer calls her work a proof of concept and notes that much more must be done before the technique can be used widely. "By comparison to state-of-the-art decoders, this is not yet a competitive method," she says. "We've only kind of scratched the surface."

—*Helen Shen*



One of the autonomous floats deployed under the ice.

EARTH SCIENCE

Ice-Diving Drones

Risky robot mission aims to explore melting Antarctic shelf

Deep below the bright, smooth surface of Antarctica's ice shelves lies a dark landscape unlike any other on earth, where inverted canyons and terraces reach far up into the ice. Fed by glaciers on land, these giant ice ledges float on the Southern Ocean's frigid waters. This year a fleet of seven underwater robots developed by the University of Washington headed into this world on a risky mission. Their goal: to help forecast sea-level rises by observing the melting process in this hidden topsy-turvy landscape, where layers of warm and cool water mix.

"We have known for about 40 years that ice shelves are intrinsically unstable," says Knut Christianson, a glaciologist on the mission and a leader of U.W.'s Future of Ice initiative. "But we do not really understand the variability of these systems, let alone how they react to a significant external [force] such as warming sea temperatures."

Previous efforts to explore the undersides of ice shelves have involved scientists drilling through them or sending robotic submarines on short trips below them. But these efforts have been restricted to small areas and brief periods—snapshots that do not necessarily reflect the full behavior of the ice-and-water system, Christianson says.

The new team of robotic explorers consists of three self-propelled drones, called Seagliders, accompanied by four drifting floats. All the vehicles contain instruments that measure temperature, pressure, turbulence and dissolved oxygen. Each of the $100,000 Seagliders will follow a several-week route under, around and back from the ice shelves. The drones swim by adjusting their buoyancy and wings to glide slowly in a programmed direction. The $30,000 floats, in contrast, are at the mercy of ocean currents; they can regulate their movement only to rise or sink.

If a drone or float rises into a crevasse or gets trapped under one of the terraces, it has no escape plan and cannot call back for help. "It's a very risky prospect," says Mick West, an engineer at the Georgia Tech Research Institute, who was not involved in the U.W. work but whose team dropped a tethered robot through Antarctica's Ross Ice Shelf in 2015.

If any drones do get lost, the U.W. scientists plan to return in 2019 to collect them. If they cannot be found, they have enough battery life to operate for another year—and any that come up later might be retrieved by other researchers and returned. But long before that, Christianson anticipates using data from the robots to improve models for the planet's rising sea levels. —*Mark Harris*

BIOLOGY

Bacterial Tape Recorder

Researchers program bacteria to record cellular memories

CRISPR is best known as being the basis of a powerful gene-editing tool. But first and foremost, it is a defense that bacteria use against viruses. Inspired by this delicate natural system, researchers have now created another scientific application for it—a tiny "tape recorder" that chronicles biological signals on strands of a bacterium's DNA.

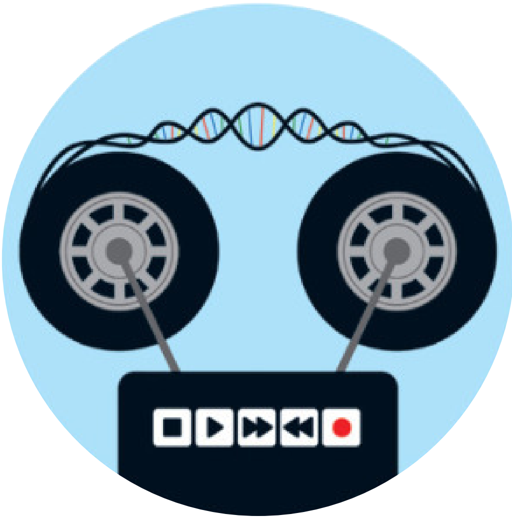
The investigators believe this microbial recorder could eventually be used for sensing abnormalities in bodily functions such as digestion; for measuring pollutant levels in oceans; or for detecting nutrient changes in soil. It works much like the natural CRISPR system in many bacteria and other single-cell organisms, except for the signals it detects.

CRISPR is a DNA sequence that makes and keeps a genetic record of viruses the bacterium encounters, commanding it to kill any that try to reinfect the bacterium or its descendants. Whereas the natural CRISPR system remembers viral DNA, the new application can track a variety of biochemical signals. For example, these bacterial recorders could detect the presence of the sugar fucose in a human's gut, indicating an infection.

When the bacterium senses a specified signal, it creates many copies of what is called trigger DNA, which get recorded on one end of its genetic "tape." The tape continues to record in the absence of the designated signal, registering the "background noise" of other pieces of DNA sloshing around in the cells. These background signals serve as time stamps on the recordings. Columbia University scientists reported the findings in a study published last December in *Science.*

The researchers suggest that a few million bacteria outfitted with copies

PAUL G. ALLEN PHILANTHROPIES



> “The DNA is writing itself in response to changes in the environment.”
> —Drew Endy, *Stanford University*

of this tool could be deployed in the human body or the environment, where they would passively record until they are recovered from feces or soil samples and the tapes can be read. Unlike most previous biological memory systems, this one is fully under the bacterial cells’ control.

“The DNA is writing itself in response to changes in the environment, whereas in the prior work you sort of had a puppeteer showing that the DNA could be written—but somebody was pulling the strings,” says Drew Endy, a synthetic biologist at Stanford University, who was not part of the study.

Although this technique has been tested only in the laboratory, the team showed it could continuously record three different signals in a population of *Escherichia coli* cells for three consecutive days.

Recording ability decreased with time, probably because operating as a tape recorder does not confer any survival benefits, Endy says. He also notes that the signal needs to be present for six hours for the tool to reliably record it, which may be too long to detect fleeting signals. Harris Wang, a synthetic biologist at Columbia and senior researcher on the study, hopes to speed that up in future work. —*Yasemin Saplakoglu*

Illustrations by Thomas Fuchs

Like humans, Eurasian blue tits sometimes get divorced.

ANIMAL BEHAVIOR

Bird Breakup

Why do some avians stay together and others part?

Humans are not the only animals that endure divorce; some birds go through it as well. A recent study reveals why members of one such species, the Eurasian blue tit, sometimes break their bond.

When ornithologists refer to "divorce," they mean that both members of a breeding pair survive to the following breeding season but end up pairing with new partners rather than reuniting. Great blue herons divorce after every breeding season, and emperor penguins split up around 85 percent of the time. In contrast, just 9 percent of mallard duck pairs call it quits, and albatrosses almost never break up. Many researchers have focused on understanding how these separations affect reproductive success, but until now few have focused on the process itself.

Behavioral ecologist Carol Gilsenan of the Max Planck Institute for Ornithology in Germany and her colleagues monitored hundreds of Eurasian blue tits for eight years, using artificial nest boxes in a protected forest in southern Germany. In their findings, published in *Animal Behaviour,* 64 percent of breeding pairs split up during the study—even though faithful pairs produced more eggs and reared more fledglings. If both members of a pair returned to their previous territory around the same time, they were more likely to reunite; if they were on different schedules, they were more likely to separate.

"If you turn up early, you can't afford to wait around," Gilsenan says. "It could be that your former mate is injured or even dead. If you wait, you may forgo a breeding opportunity, so you need to pair up." Adult mortality in blue tits is extremely high—around 50 percent—so the bird that returns first is more likely to breed again by finding a new partner rather than risk being left out entirely. The birds seem to be simply playing the odds.

The researchers also discovered that if pairs maintained contact outside the breeding season, they were more likely to have synchronized schedules and therefore to remain faithful to each other.

Josh A. Firth, a zoologist at the University of Oxford, who was not involved with the study, says this analysis apparently rules out a number of other possible causes of avian divorce, including low reproductive success rates, infidelity, and genetic or behavioral compatibility. "In wild animal populations," he says, "divorce can be driven by consequential effects—almost accidentally."

—Jason G. Goldman

ECOLOGY

Fish Frenzy

Gulf corvina orgies produce one of the loudest sounds in the ocean

When Gulf corvina mate, they are not shy about making noise. Every year the species' entire population gathers off the coast of Mexico to spawn. Like crickets, cicadas and frogs, male corvina produce a thumping love song that likely acts as a come-hither signal for females. The resulting underwater din turns out to be the highest-decibel fish noise ever recorded, even rivaling whale song—making it one of the loudest naturally produced sounds in the ocean, according to a study published last December in *Biology Letters.*

"At first, we thought our equipment was broken," says co-author Brad E. Erisman, a fisheries ecologist at the University of Texas at Austin. "No one anticipated fish would be this loud."

Erisman and his colleagues traveled to the Colorado River Delta, which empties into the Sea of Cortez. It is here and only here that Gulf corvina come to spawn, probably because the delta's extreme 25-foot-plus (eight-meter) tides help to flush their fertilized eggs out to sea. The researchers measured the sound produced by the fish using an echo sounder (a sonar unit) and a hydrophone (underwater microphone). Based on the vocalizations, they estimated there were as many as 1.5 million fish in a 17-mile (27-kilometer) stretch of river

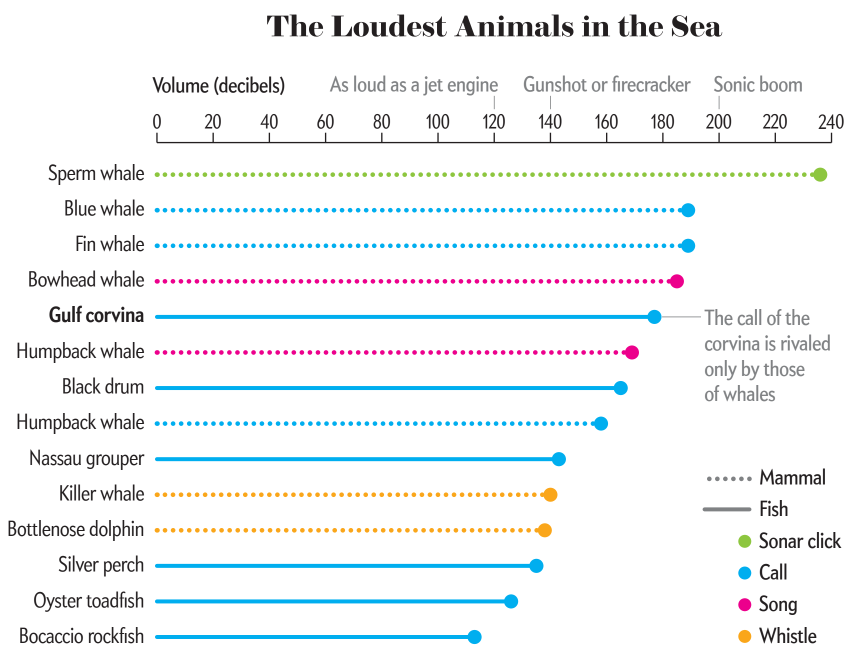
FABRIZIO MOGLIA *Getty Images (birds);* OCTAVIO ABURTO *(corvina)*

channel during one peak spawning day. The total population is likely much higher, the scientists say.

More than 1,000 fish species produce sounds, but the researchers found the Gulf corvina to be in a class by itself. At 177 decibels, an individual corvina's mating call is louder than the equivalent of standing next to the stage at a rock concert. The noise is so intense that it may harm the hearing of other marine animals caught up in the action. "This paper is solid, and the findings are convincing," says Stephen Simpson, a marine biologist and fish ecologist at the University of Exeter in England, who was not involved in the research.

The fact that the Gulf corvina gather in a single estuary to breed year after year makes them highly vulnerable to overfishing. "Lots of fishes are heavily exploited and endangered because of this amazing behavior where they come together to spawn," Erisman says. In the age of gillnets and trawls, the evolutionary advantages of group spawning can paradoxically imperil the species' survival. —*Rachel Nuwer*

SOURCE: "A SOUND WORTH SAVING: ACOUSTIC CHARACTERISTICS OF A MASSIVE FISH SPAWNING AGGREGATION," BY BRAD E. ERISMAN AND TIMOTHY J. ROWELL, IN *BIOLOGY LETTERS*, VOL. 13, NO. 12; DECEMBER 2017



The decibel scale of sound intensity is logarithmic. This means that a sound measuring 20 decibels is actually 100 times more powerful than zero (near total silence); 30 decibels is 1,000 times more powerful; and so on. At 177 decibels, the gulf corvina's mating call is so loud that extended exposure to it may harm the hearing of nearby animals.

Graphic by Amanda Montañez

PSYCHOLOGY

Ineffective Geniuses?

People with very high IQs can be perceived as worse leaders

Intelligence makes for better leaders—from undergraduates to executives to presidents—according to multiple studies. It certainly makes sense that handling a market shift or legislative logjam requires cognitive oomph. But new research on leadership suggests that, at a certain point, having a higher IQ can be viewed as harmful.

Although previous research has shown that groups with smarter leaders perform better by objective measures, some studies have hinted that followers might subjectively view leaders with stratospheric intellect as less effective. Decades ago Dean Simonton, a psychologist the University of California, Davis, proposed that brilliant leaders' words may simply go over people's heads, their solutions could be more complicated to implement and followers might find it harder to relate to them. Now Simonton and two colleagues have finally tested that idea, publishing their results in the July 2017 issue of the *Journal of Applied Psychology.*

The researchers looked at 379 male and female business leaders in 30 countries, across fields that included banking, retail and technology. The managers took IQ tests (an imperfect but robust predictor of performance in many areas), and each was rated on leadership style and effectiveness by an average of eight co-workers. IQ positively correlated with ratings of leader effectiveness, strategy formation, vision and several other characteristics—up to a point. The ratings peaked at an IQ of around 120, which is higher than roughly 80 percent of office workers. Beyond that, the ratings declined. The researchers suggest the "ideal" IQ could be higher or lower in various fields, depending on whether technical versus social skills are more valued in a given work culture.

"It's an interesting and thoughtful paper," says Paul Sackett, a psychology professor at the University of Minnesota, who was not involved in the research. "To me, the right interpretation of the work would be that it highlights a need to understand what high-IQ leaders do that leads to lower perceptions by followers. The wrong interpretation would be, 'Don't hire high-IQ leaders.' "

The study's lead author, John Antonakis, a psychologist at the University of Lausanne in Switzerland, suggests leaders should use their intelligence to generate creative metaphors that will persuade and inspire others—the way former U.S. President Barack Obama did. "I think the only way a smart person can signal their intelligence appropriately and still connect with the people," Antonakis says, "is to speak in charismatic ways." —*Matthew Hutson*

TECH

"I'm Sorry, Dave"

Debugging software spots AI's mistakes

As artificial-intelligence systems become widespread, the chances grow that their glitches will have dangerous consequences. For example, scientists at the Massachusetts Institute of Technology recently fooled a Google-trained AI program into identifying a plastic toy turtle as a rifle. If a future robot cop or soldier made such an error, the results could be tragic. But researchers are now developing tools to sniff out potential flaws among the billions of virtual "brain cells" that make up such systems.

Many image-recognition programs, car autopilots and other forms of AI use artificial neural networks, in which components dubbed "neurons" are fed data and cooperate to solve a problem—such as spotting obstacles in the road. The network "learns" by repeatedly adjusting the connections between its neurons and trying the problem again. Over time, the system determines which neural connection patterns are best at computing solutions. It then adopts these as defaults, mimicking how the human brain learns.

A key challenge of this technology is that developers often do not know how networks arrive at their decisions. This can make it hard to figure out what went wrong when a mistake is made, says Junfeng Yang, a computer scientist at Columbia University and a co-author of a new study presented last October at a symposium in Shanghai.

Yang and his colleagues created DeepXplore, a program designed to debug AI systems by reverse engineering their learning processes. It tests a neural network with a wide range of confusing real-world inputs and tells the network when its responses are wrong so that it can correct itself. For example, DeepXplore could determine if a camera image fed to a car-driving AI system mistakenly steered a vehicle toward pedestrians. The debugging tool also monitors which neurons in a network are active and tests each one individually. Previous AI-debugging tools could not tell if every neuron had been checked for errors, Yang says.

In tests on 15 state-of-the-art neural networks—including some used in self-driving cars and computer malware detection—DeepXplore discovered thousands of bugs missed by earlier technology. It boosted the AI systems' overall accuracy by 1 to 3 percent on average, bringing some systems up to 99 percent. DeepXplore's technique could help developers build "more accurate and more reliable" neural networks, says Shan Lu, a computer scientist at the University of Chicago, who did not take part in the new research. This approach, Lu adds, "in turn can benefit many scientific research disciplines and our daily lives." —*Charles Q. Choi*

GETTY IMAGES (*baby and crosshairs*)

Mola alexandrini and human.

HASAMA UNDERWATER PARK

TAXONOMY

Fishy Behemoth

World's largest bony fish was previously misidentified

Scientists have long thought the ocean sunfish (*Mola mola*) was the largest of the bony fishes, a group of animals with skeletons made of bone instead of cartilage. It turns out they were wrong. A research team reported in January in *Ichthyological Research* that the biggest is, in fact, the bump-head sunfish (*Mola alexandrini*), specimens of which had previously been misidentified as *M. mola*.

Etsuro Sawai, a biologist at Hiroshima University in Japan, led the group that reexamined hundreds of sunfish specimens and scientific records from around the world. Bump-head sunfish, distinguishable by small lumps on the head and chin, can grow up to 10 feet (three meters) long and weigh more than 5,000 pounds (2,300 kilograms).

The study suggests there may be "many more such instances of misidentification of animal species"—especially considering that the sunfish is relatively large and hard to miss—says Byrappa Venkatesh, a geneticist at the Institute of Molecular and Cell Biology in Singapore, who was not involved in the new research.

Co-author Marianne Nyegaard, an ichthyologist at Australia's Murdoch University, says this type of clarification is vital in biology and "important in understanding, for example, the ecological consequences of climate change." Temperature changes could shift the known ranges of different species that previously were not correctly distinguished.

—*Doug Main*

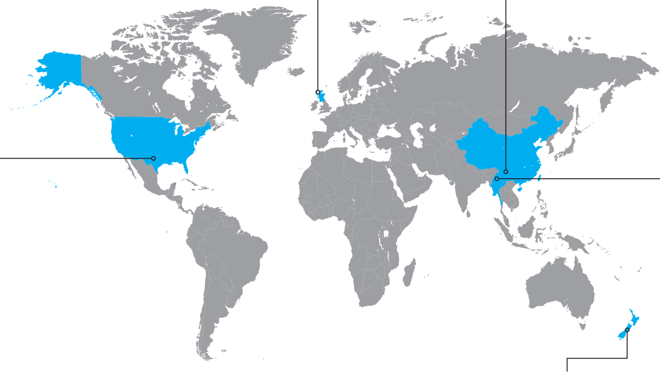
IN THE NEWS

Quick Hits

SCOTLAND
On the Isle of Skye, geologists discovered evidence of a previously unknown meteor impact that occurred 60 million years ago. Rocks discovered at the bottom of lava flows contained two minerals—vanadium- and niobium-rich osbornite—that had never before been detected on Earth.

CHINA
A cave in Yunnan province houses bats that carry a type of coronavirus resembling the strain that triggered the global SARS outbreak of 2003, killing hundreds of people. Researchers hope studying these bats could help them develop a vaccine to prevent future epidemics.

U.S.
An estimated 34 trillion gallons of water—more than 50 million Olympic-size swimming pools' worth—fell on Texas last August during Hurricane Harvey, according to a recent analysis. Scientists think the extreme event was 15 percent more intense than normal because of climate change.



MYANMAR
A 99-million-year-old tick clinging to a dinosaur feather was found preserved in a piece of amber from a private collection in northern Myanmar (formerly Burma). The fossil provides the first evidence that these parasitic insects also pestered the dinosaurs.

ANTARCTICA
The diversity and numbers of species residing underneath the Ross Ice Shelf have greatly increased since 2009, scientists say. They hypothesize that climate change thinned the ice, letting in more light and increasing the growth of algae, which feeds diverse species.

NEW ZEALAND
Scientists have excavated the bones of an extinct giant penguin, *Kumimanu biceae*. The bird, which lived 60 million to 55 million years ago, stood nearly six feet tall and weighed more than 200 pounds.

—Yasemin Saplakoglu

For more details, visit www.ScientificAmerican.com/mar2018/advances

Claudia Wallis is an award-winning science journalist whose work has appeared in the *New York Times, Time, Fortune* and the *New Republic.* She was science editor at *Time* and managing editor of *Scientific American Mind.*

A Perfectly Avoidable Crisis

Bone fractures are rife after age 50. Can't we do more about osteoporosis?

By Claudia Wallis

Like many people—and sadly, that includes many doctors—I had some very wrong ideas about osteoporosis. Weight-bearing exercise, calcium and vitamin D, I figured, are all we really need to keep age-related bone loss in check. Drugs that treat the disease aren't worth the risk because of hideous side effects (such as a disintegrating jawbone!). Bone density tests are something of a scam, needlessly scaring a lot of people (especially middle-aged women like me) into taking those dreaded drugs.

And then there were the dots I somehow failed to connect. For instance, it is no secret that hip fractures are a massive problem for older people, striking more than 300,000 annually in the U.S. alone, half of whom will never walk again without assistance and a quarter of whom will be dead within a year. But somehow I never realized that most of this death and disability can be attributed to the steady skeletal erosion of osteoporosis, a disease that, it turns out, is pretty darn treatable.

Unfortunately, false ideas like mine have led us to a perfectly avoidable health crisis. Let me flip the calendar back to 1995, the year when the first drug for osteoporosis, alendronate (brand name: Fosamax), was approved for sale and roughly the time when x-ray-based bone density tests became widely available. Fosamax was the first of several bisphosphonate drugs that work by slowing the turnover of bone cells. Research shows that they cut the risk of fracture by 20 to 50 percent.

Doctors embraced the new drugs, and U.S. hip fracture rates began to decline (although you cannot prove cause and effect). Arguably, physicians were a little too enthusiastic. A new diagnosis, "osteopenia"—low bone density that falls short of osteoporosis—was popularized and often treated, particularly in women going through menopause, when bone loss is fastest. "A lot of us were almost evangelical," concedes endocrinologist Ethel Siris of Columbia University Medical Center.

Then, around 2005, came published reports of two rare but terrifying side effects: osteonecrosis of the jaw and a bizarre breaking of the leg bone called atypical femoral fracture (AFF). A chill descended on the field. Use of oral bisphosphonates fell by 50 percent between 2008 and 2012. The U.S. hip fracture rate plateaued, leading to 11,000 more fractures between 2013 and 2015 than predicted, according to a new study by Siris and her colleagues.

Yet research shows that both dreaded side effects are, as Siris puts it, "rare, rare, and I'm going to say it three times, rare"—with about one case per 10,000 to 100,000 patients. Clinicians have also learned more about who is vulnerable and, in the case of AFF, how to detect warning signs. Further, new drugs have emerged that do not have the same risks.

But since the scare, precious ground has been lost in protecting the most vulnerable group: older patients with fractures. Ideally, all patients over 50 who break a wrist, shoulder, hip or vertebra should be checked for osteoporosis and treated, if warranted. In reality, only about 20 percent are, although 15 years ago 40 percent of hip fracture patients got this kind of workup.

Doctors who study and treat osteoporosis are practically apoplectic about the trend. They point to research showing that if you have one "fragility fracture," you face nearly three times the usual risk of having another one within the year. Nearly half of people who break a hip have previously broken another bone. In short, it's pretty crazy not to look for and treat osteoporosis with the first fracture. Douglas P. Kiel, a professor at Harvard Medical School, calls it "tantamount to public health malpractice."

Why aren't testing and treatment happening? Many reasons, on top of the side effect issue. No single specialty owns osteoporosis. Orthopedic surgeons who deal with fractures have no training and little incentive to treat it, nor does Medicare require a bone density evaluation after a bone fracture. Nursing homes, which often manage the care of patients with broken hips, tend to let things lie once the fracture is treated, Siris says. Plus, a flurry of competing recommendations and misconstrued studies have left the average doctor "a little bewildered about who should be getting what treatment and for how long," says endocrinologist Steven Harris, a clinical professor of medicine at the University of California, San Francisco.

Finally, there's the simple fact that this is a silent disease. We don't feel our bones degrading; there's no pain until they crack. But it's a sad mistake to wait. SA

Illustration by Celia Krampien

David Pogue is the anchor columnist for Yahoo Tech and host of several *NOVA* miniseries on PBS.

Video Disorientation

We see horizontally but tend to hold our phones vertically

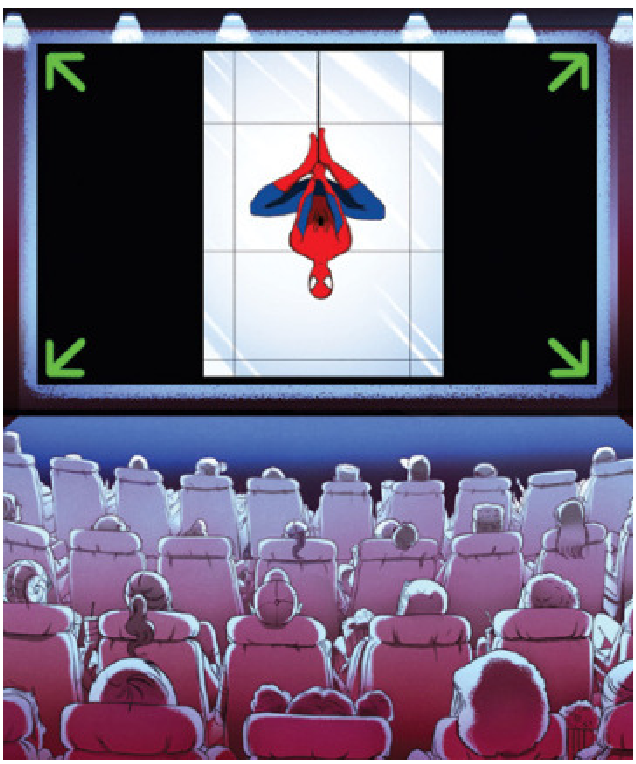
By David Pogue

In the world of electronics, the term "aspect ratio" refers to the shape of your screen. Today's high-definition television picture has a 16:9 aspect ratio—a rectangle with those proportions. The older, standard TV picture had a 4:3 aspect ratio—not quite square but squarish. Films, IMAX movies and photographs all have aspect-ratio standards of their own.

This cacophony of conflicting shapes can lead to some ugly results. Remember watching widescreen movies on standard TVs? Much of your screen was filled by horizontal, black "letterbox" bars above and below the picture. And on high-def TVs, watching old shows requires big, black "pillarbox" bars on either side of the square picture.

If that seemed confusing, though, don't look now, because we've just entered the age of aspect-ratio hell.

The culprit is smartphones. We now watch more video on our mobile gadgets than we do on TVs and computers. And guess what? A phone's screen has portrait orientation—a tall, thin rectangle. It's the worst possible shape for showing wide (landscape-orientation) images. Movies and TV shows play as a tiny slit of screen on an ocean of black.



I know what you're screaming: "But we can turn the phone 90 degrees, numbskull!" Yes, we *can*. But we don't. There's a certain hassle, an inconvenience, a discomfort, in turning your phone. You move from One-Hand Land to Two-Hand Land. Fewer and fewer people bother turning their phones to watch widescreen videos—72 percent of millennials don't, in fact.

Software and video producers are scrambling to accommodate the New Normal—the vertical-aspect-ratio screen. Snapchat started it; its 178 million fans overwhelmingly take and share vertically shot photos and videos. Facebook now presents vertical videos in your scrolling feed without your having to tap to expand them; advertisers report that their vertical Facebook ads get much more attention from viewers than square ones. Instagram, YouTube and Twitter have updated their apps to handle vertical videos, too.

Professional outfits are now shooting vertically to match the trend. Vervid is a new app that exists purely to play vertical videos. Vertical Cinema (www.verticalcinema.org) is a vertical-video film festival, in which the movie screen is hung vertically. Yahoo (my employer) is developing a new subscription service whose shows are all shot vertically. The upshot: Because of their ubiquity, we now watch most of our videos on smartphones; because of ergonomics, we hold the phone vertically; because we hold it that way, professional videos are now being produced to match. Okay, great.

But all of this leaves us in a massive aspect-ratio pickle. Our TVs and computer screens are still horizontal. So what happens when a vertical cellphone video plays on a TV or a laptop? You've surely seen it: broadcasters gamely try to fill the empty pillarbox areas with blurry copies of the main video. It's awful. Conversely, the entire archive of movies and hi-def TV is horizontal. Those videos will never look even close to right on vertical screens.

Then there's the issue of what's *in* the videos. Fans of vertical video argue that vertical shots do better justice to buildings, trees, mountains and scenes of a single upright person. Instead of just head and shoulders, you're seeing torso and hands, too.

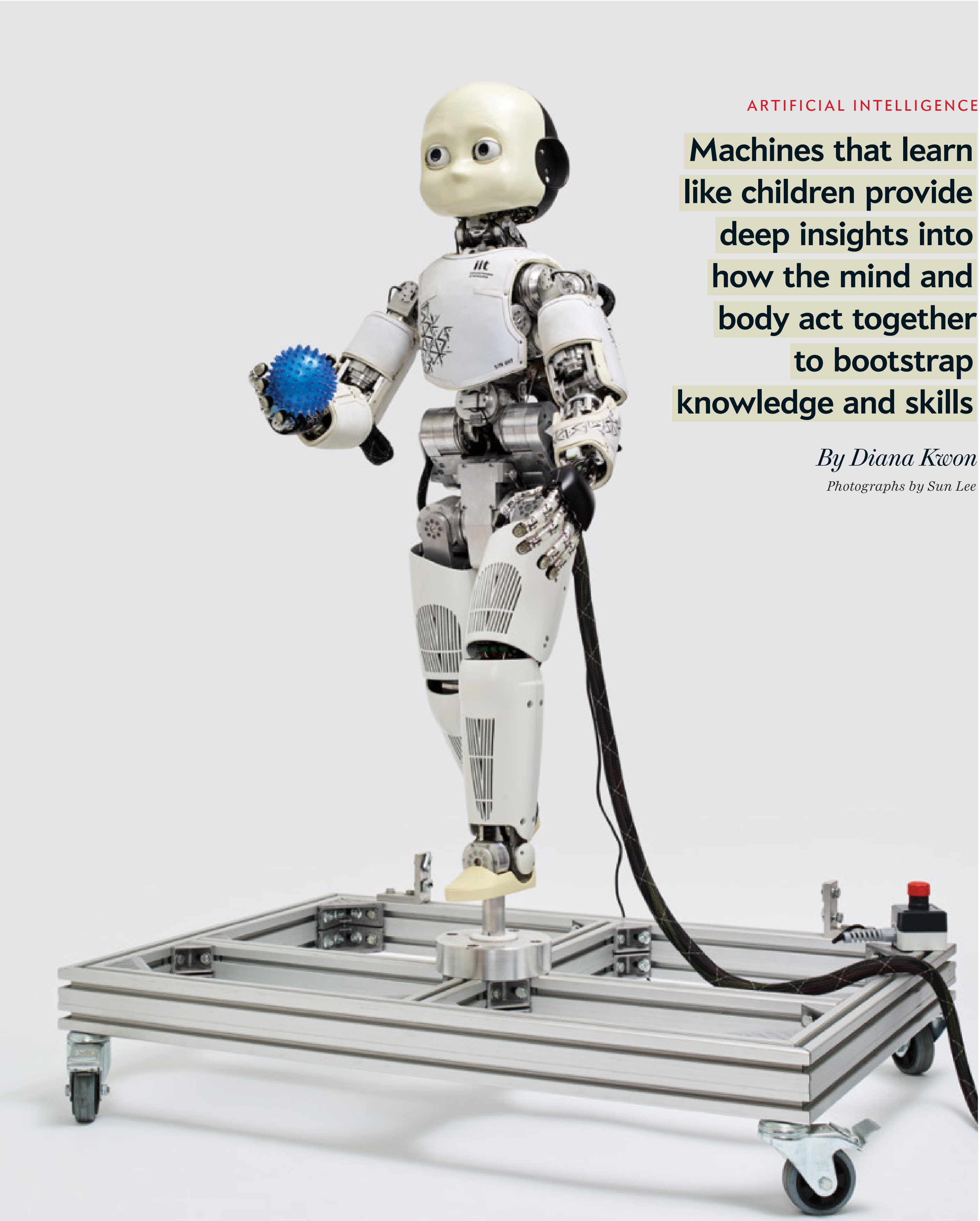
There's a good reason our standards for movies and TV are horizontal: our eyes are arranged horizontally, and we spend our lives on a horizontal plane. A horizontal format is far superior to vertical at showing most things in daily life. For example, scenes with *more* than one person and just about anything in motion.

In other words, we're witnessing a titanic crash between our eyes and our hands, between logic and ergonomics, between the old and the new. What's the resolution? Young people will never turn their phones sideways; on the other hand, TVs, movie theaters and computer screens won't soon be designed vertically. This isn't a temporary transitional problem, either, as it was when we moved from standard to hi-def TV; this time the two formats will have to coexist. For once, it's easy to predict the shape(s) of things to come—and it's kind of a mess. SA

SCIENTIFIC AMERICAN ONLINE
READ MORE ABOUT THE VERTICAL/HORIZONTAL VIDEO PROBLEM: scientificamerican.com/mar2018/pogue

Illustration by Jay Bendt

Self-Taught Robots



ARTIFICIAL INTELLIGENCE

Machines that learn like children provide deep insights into how the mind and body act together to bootstrap knowledge and skills

By Diana Kwon

Photographs by Sun Lee

Diana Kwon is a journalist with a master's degree in neuroscience from McGill University. She writes about health and the life sciences from Berlin.

DEON, A FICTIONAL ENGINEER IN the 2015 sci-fi film *Chappie,* wants to create a machine that can think and feel. To this end, he writes an artificial-intelligence program that can learn like a child. Deon's test subject, Chappie, starts off with a relatively blank mental slate. By simply observing and experimenting with his surroundings, he acquires general knowledge, language and complex skills—a task that eludes even the most advanced AI systems we have today.

To be sure, certain machines already exceed human abilities for specific tasks, such as playing games like Jeopardy, chess and the Chinese board game Go. In October 2017 British company DeepMind unveiled AlphaGo Zero, the latest version of its AI system for playing Go. Unlike its predecessor AlphaGo, which had mastered the game by mining vast numbers of human-played games, this version accumulated experience autonomously, by competing against itself. Despite its remarkable achievement, AlphaGo Zero is limited to learning a game with clear rules—and it needed to play millions of times to gain its superhuman skill.

In contrast, from early infancy onward our offspring develop by exploring their surroundings and experimenting with movement and speech. They collect data themselves, adapt to new situations and transfer expertise across domains.

Since the beginning of the 21st century, roboticists, neuroscientists and psychologists have been exploring ways to build machines that mimic such spontaneous development. Their collaborations have resulted in androids that can move objects, acquire basic vocabulary and numerical abilities, and even show signs of social behavior. At the same time, these AI systems are helping psychologists understand how infants learn.

PREDICTION MACHINE

OUR BRAINS are constantly trying to predict the future—and updating their expectations to match reality. Say you encounter your neighbor's cat for the first time. Knowing your own gregarious puppy, you expect that the cat will also enjoy your caresses. When you reach over to pet the creature, however, it scratches you. You update your theory about cuddly-looking animals—surmising, perhaps, that the kitty will be friendlier if you bring it a treat. With goodies in hand, the cat indeed lets you stroke it without inflicting wounds. Next time you encounter a furry feline, you offer a tuna tidbit before trying to touch it.

In this manner, the higher processing centers in the brain continually refine their internal models according to the signals received from the sensory organs. Take our visual systems, which are highly complex. The nerve cells in the eye process basic features of an image before transferring this information to higher-level regions that interpret the overall meaning of a scene. Intriguingly, neural connections also run in the other direction: from high-level processing centers, such as areas in the parietal or temporal cortices, to low-level ones such as the primary visual cortex and the lateral geniculate nucleus [*see box on page 30*]. Some neuroscientists believe that these "downward" connections carry the brain's predictions to lower levels, influencing what we see.

Crucially, the downward signals from the higher levels of the brain continually interact with the "upward" signals from the senses, generating a prediction error: the difference between what we expect and what we experience. A signal conveying this discrepancy returns to the higher levels, helping to refine internal models and generating fresh guesses, in an unending loop. "The prediction error signal drives the system toward estimates of what's really out there," says Rajesh P. N. Rao, a computational neuroscientist at the University of Washington.

While Rao was a doctoral student at the University of Rochester, he and his supervisor, computational neuroscientist Dana H. Ballard, now at the University of Texas at Austin, became the first to test such predictive coding in an artificial neural network. (A class of computer algorithms modeled on the human brain, neural networks incrementally adapt internal parameters

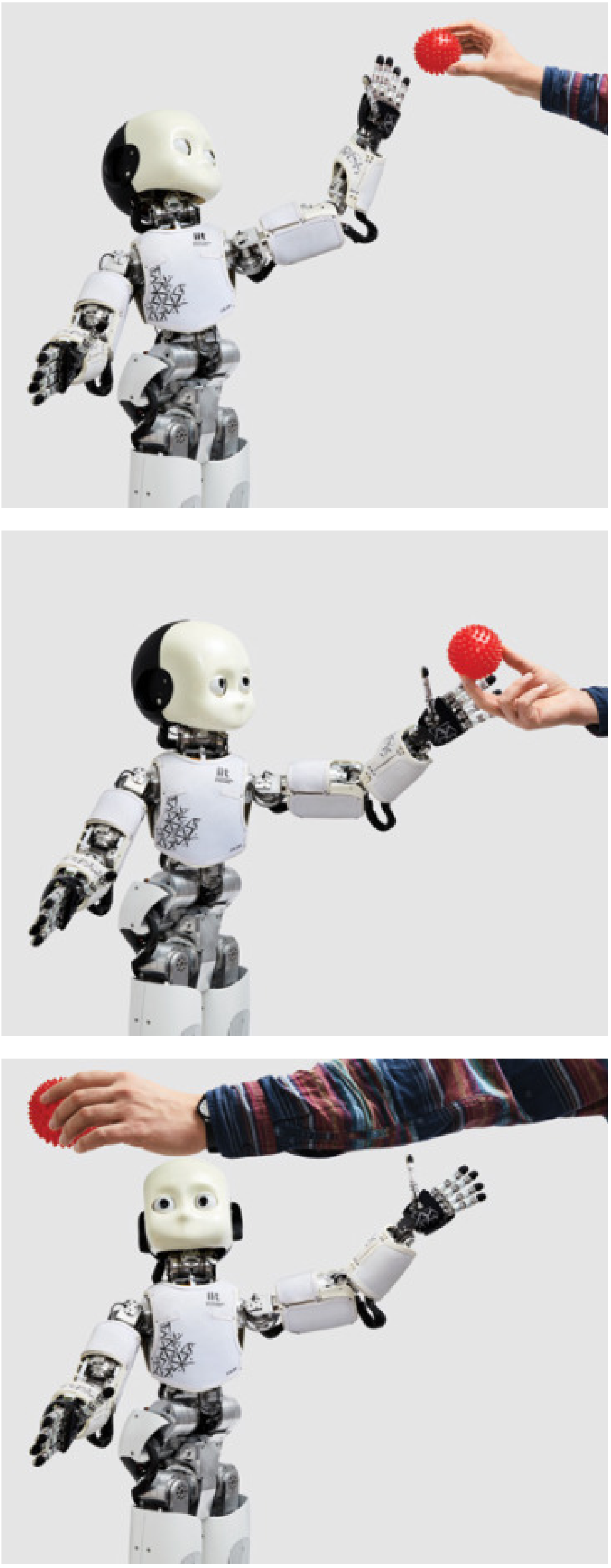
IN BRIEF

Infants learn autonomously, by experimenting with their bodies and playing with objects.

Roboticists are programming androids with algorithms that enable them to learn like children.

Studies with such machines are transforming robotics and providing insights into child development.

to generate the required output from a given input.) In this computational experiment, published in 1999 in *Nature Neuroscience,* the researchers simulated neuronal connections in the visual cortex—complete with downward connections carrying forecasts and upward connections bringing sensory signals from the outside world. After training the network using pictures of nature, they found that it could learn to recognize key features of an image, such as a zebra's stripes.



ICUB, an android being studied at the University of Plymouth in England, can learn new words, such as "ball," more easily if the experimenter consistently places the object at the same location while naming it.

COUNTING WITH FINGERS

A FUNDAMENTAL DIFFERENCE between us and many present-day AI systems is that we possess bodies that we can use to move about and act in the world. Babies and toddlers develop by testing the movements of their arms, legs, fingers and toes and examining everything within reach. They autonomously learn how to walk, talk, and recognize objects and people. How youngsters are able to do all this with very little guidance is a key area of investigation for both developmental psychologists and roboticists. Their collaborations are leading to surprising insights—in both fields.

In a series of pioneering experiments starting in the late 1990s, roboticist Jun Tani, then at Sony Computer Science Laboratories, and others developed a prediction-based neural network for learning basic movements and tested how well these algorithms worked in robots. The machines, they discovered, could attain elementary skills such as navigating simple environments, imitating hand movements, and following basic verbal commands like "point" and "hit."

More recently, roboticist Angelo Cangelosi of the University of Plymouth in England and Linda B. Smith, a developmental psychologist at Indiana University Bloomington, have demonstrated how crucial the body is for procuring knowledge. "The shape of the [robot's] body, and the kinds of things it can do, influences the experiences it has and what it can learn from," Smith says. One of the scientists' main test subjects is iCub, a three-foot-tall humanoid robot built by a team at the Italian Institute of Technology for research purposes. It comes with no preprogrammed functions, allowing scientists to implement algorithms specific to their experiments.

In a 2015 study, Cangelosi, Smith and their colleagues endowed an iCub with a neural network that gave it the ability to learn simple associations and found that it acquired new words more easily when objects' names were consistently linked with specific bodily positions. The experimenters repeatedly placed either a ball or a cup to the left or right of the android, so that it would associate the objects with the movements required to look at it, such as tilting its head. Then they paired this action with the items' names. The robot was better able to learn these basic words if the corresponding objects appeared in one specific location rather than in multiple spots.

Interestingly, when the investigators repeated the experiment with 16-month-old toddlers, they found similar results: relating objects to particular postures helped small children learn word associations. Cangelosi's laboratory is developing this technique to teach robots more abstract words such as "this" or "that," which are not linked to specific things.

Using the body can also help children and robots gain basic numerical skills. Studies show, for instance, that youngsters who have difficulty mentally representing their fingers also tend to have weaker arithmetic abilities. In a 2014 study, Cangelosi and

his team discovered that when the robots were taught to count with their fingers, their neural networks represented numbers more accurately than when they were taught using only the numbers' names.

CURIOSITY ENGINES

NOVELTY ALSO HELPS children learn. In a 2015 *Science* paper, researchers at Johns Hopkins University reported that when infants encounter the unknown, such as a solid object that appears to move through a wall, they explore their violated expectations. In prosaic terms, their in-built drive to reduce prediction errors aids their development.

Pierre-Yves Oudeyer, a roboticist at INRIA, the French national institute for computer science, believes that the learning process is more complex. He holds that kids actively, and with surprising sophistication, seek out those objects in their environment that provide greater opportunities to learn. A toddler, for example, will likely choose to play with a toy car rather than with a 100-piece jigsaw puzzle—arguably because her level of knowledge will allow her to generate more testable hypotheses about the former.

To test this theory, Oudeyer and his colleagues endowed robotic systems with a feature they call intrinsic motivation, in which a decrease in prediction error yields a reward. (For an intelligent machine, a reward can correspond to a numerical quantity that it has been programmed to maximize through its actions.) This mechanism enabled a Sony AIBO robot, a small, puppylike machine with basic sensory and motor abilities, to autonomously seek out tasks with the greatest potential for learning. The robotic puppies were able to acquire basic skills, such as grasping objects and interacting vocally with another robot, without having to be programmed to achieve these specific ends. This outcome, Oudeyer explains, is "a side effect of the robot exploring the world, driven by the motivation to improve its predictions."

Remarkably, even though the robots went through similar stages of training, chance played a role in what they learned. Some explored a bit less, others a bit more—and they ended up knowing different things. To Oudeyer, these varied outcomes suggest that even with identical programming and a similar educational environment, robots may attain different skill levels—much like what happens in a typical classroom.

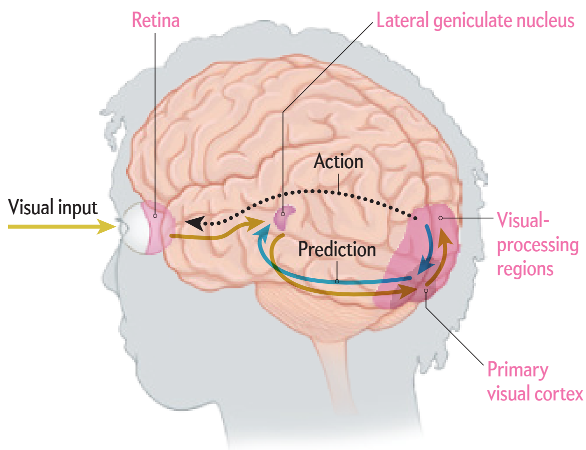
More recently, Oudeyer's group used computational simulations to show that robotic vocal tracts equipped with these predictive algorithms (and the proper hardware) could also learn basic elements of language. He is now collaborating with Jacqueline Gottlieb, a cognitive neuroscientist at Columbia University, to investigate whether such prediction-driven intrinsic motivation underlies the neurobiology of human curiosity as well. Probing these models further, he says, could help psychologists understand what happens in the brains of children with developmental disabilities and disorders.

ALTRUISTIC ANDROIDS

OUR BRAINS ALSO TRY to forecast the future when we interact with others: we constantly attempt to deduce people's intentions and anticipate what they might say next. Intriguingly, the drive to reduce prediction errors can, in and of itself, induce elementary social behavior, as roboticist Yukie Nagai and her colleagues demonstrated in 2016 at Osaka University in Japan.

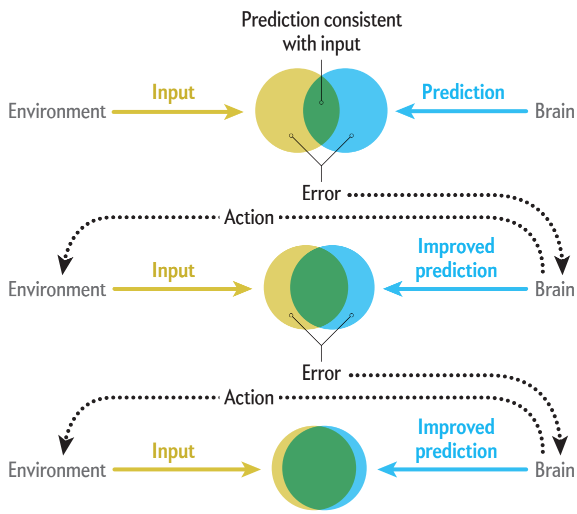
Predictive Brain

Our minds are prediction machines, using prior experience and knowledge to make sense of the deluge of information coming from our surroundings. Many neuroscientists and psychologists believe that nearly everything we do—perception, action and learning—relies on making and updating expectations.



Visual Processing

The brain's anatomy supports the idea of predictive processing. The visual cortex, for example, receives inputs from the eye, but connections also run in the other direction. Neuroscientists believe that these "downward" connections, from higher levels of the brain to the lower (such as the primary visual cortex and the lateral geniculate nucleus), carry predictions. These meet with the sensory input to generate a prediction error: the difference between what you expect and what you see. A signal coding this discrepancy returns to the higher levels of the brain. Other downward signals send commands to move the eye muscles, adjusting what we see.



Cascade of Predictions

When the brain generates a prediction error, it uses this information to update its expectations and select actions that will help resolve the discrepancy between beliefs and reality. For example, if an individual cannot determine what an object is simply by looking at it, the brain might send a command to pick up the item and examine it to gather more information.

Illustration by Mesa Schumacher (brain) and Amanda Montañez (cascade diagram)

The researchers found that even when iCub was not programmed with an intrinsic ability to socialize, the motivation to reduce prediction errors alone led it to behave in a helpful way. For example, after the android was taught to push a toy truck, it might observe an experimenter failing to complete that same action. Often it would move the object to the right place—simply to increase the certainty of the truck being at a given location. Young children might develop in a similar way, believes Nagai, who is currently at the National Institute of Information and Communications Technology in Japan. "The infant doesn't need to have the intention to help other persons," she argues: the motivation to minimize prediction error can alone initiate elementary social abilities.

Predictive processing may also help scientists understand developmental disorders such as autism. According to Nagai, certain autistic individuals may have a higher sensitivity to prediction errors, making incoming sensory information overwhelming. That could explain their attraction to repetitive behavior, whose outcomes are highly predictable.

Harold Bekkering, a cognitive psychologist at Radboud University in the Netherlands, believes that predictive processing could also help explain the behavior of people with attention deficit hyperactivity disorder. According to this theory, autistic individuals prefer to protect themselves from the unknown, whereas those who have trouble focusing are perpetually attracted to unpredictable stimuli in their surroundings, Bekkering explains. "Some people who are sensitive to the world explore the world, while other people who are too sensitive for the world shield themselves," he suggests. "In a predictive coding framework, you can very nicely simulate both patterns." His lab is currently working on using human brain imaging to test this hypothesis.

Nagai hopes to assess this theory by conducting "cognitive mirroring" studies in which robots, equipped with predictive learning algorithms, will interact with people. As the robot and person communicate using body language and facial expressions, the machine will adjust its behaviors to match its partner—thus reflecting the person's preference for predictability. In this way, experimenters can use robots to model human cognition—then examine its neural architecture to try to decipher what is going on inside human heads. "We can externalize our characteristics into robots to better understand ourselves," Nagai says.

The drive to reduce prediction errors can, in and of itself, induce elementary social behavior in a robot.

ROBOTS OF THE FUTURE

STUDIES OF ROBOTIC CHILDREN have thus helped answer certain key questions in psychology, including the importance of predictive processing, and of bodies, in cognitive development. "We have learned a huge amount about how complex systems work, how the body matters, [and] about really fundamental things like exploration and prediction," Smith says.

Robots that can develop humanlike intelligence are far from becoming a reality, however: Chappie still belongs in the realm of science fiction. To begin with, scientists need to overcome technical hurdles, such as the brittle bodies and limited sensory capabilities of most robots. (Advances in areas such as soft robotics and robot vision may help this happen.) Far more challenging is the incredible intricacy of the brain itself. Despite efforts on many fronts to model the mind, scientists are far from engineering a machine to rival it. "I completely disagree with people who say that in 10 or 20 years we'll have machines with human-level intelligence," Oudeyer says. "I think it's showing a profound misunderstanding of the complexity of human intelligence."

Moreover, intelligence does not merely require the right machinery and circuitry. A long line of research has shown that caregivers are crucial to children's development. "If you ask me if a robot can become truly humanlike, then I'll ask you if somebody can take care of a robot like a child," Tani says. "If that's possible, then yes, we might be able to do it, but otherwise, it's impossible to expect a robot to develop like a real human child."

The process of gradually accumulating knowledge may also be indispensable. "Development is a very complex system of cascades," Smith says. "What happens on one day lays the groundwork for [the next]." As a result, she argues, it might not be possible to build human-level artificial intelligence without somehow integrating the step-by-step process of learning that occurs throughout life.

Soon before his death, Richard Feynman famously wrote: "What I cannot create, I do not understand." In Tani's 2016 book, *Exploring Robotic Minds,* he turns his concept around, saying, "I can understand what I can create." The best way to understand the human mind, he argues, is to synthesize one.

One day humans may succeed in creating a robot that can explore, adapt and develop just like a child, perhaps complete with surrogate caregivers to provide the affection and guidance needed for healthy growth. In the meantime, childlike robots will continue to provide valuable insights into how children learn—and reveal what might happen when basic mechanisms go awry. SA

MORE TO EXPLORE

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How Evolution May Work through Curiosity-Driven Developmental Process. Pierre-Yves Oudeyer and Linda B. Smith in *Topics in Cognitive Science,* Vol. 8, No. 2, pages 492–502; April 2016.

FROM OUR ARCHIVES

Bipedal Metal. John Pavlus; July 2016.

scientificamerican.com/magazine/sa

ORBITING A RED DWARF, this imagined planet has its own moon. Both are bathed in a warm glow from the star and its flares.

PLANETARY SCIENCE

SHADOWS OF OTHER

Two telescopes due to launch this year should reveal a host of new exoplanets

By Joshua N. Winn

Illustrations by Ron Miller

WORLDS

IN BRIEF

The world's most prolific planet-hunting satellite, NASA's Kepler spacecraft, is preparing to shut down, but several new missions targeting exoplanets are due to launch this year.

The Transiting Exoplanet Survey Satellite (TESS) and the Characterising Exoplanet Satellite (CHEOPS) will both search for signs of other worlds crossing in front of their parent stars.

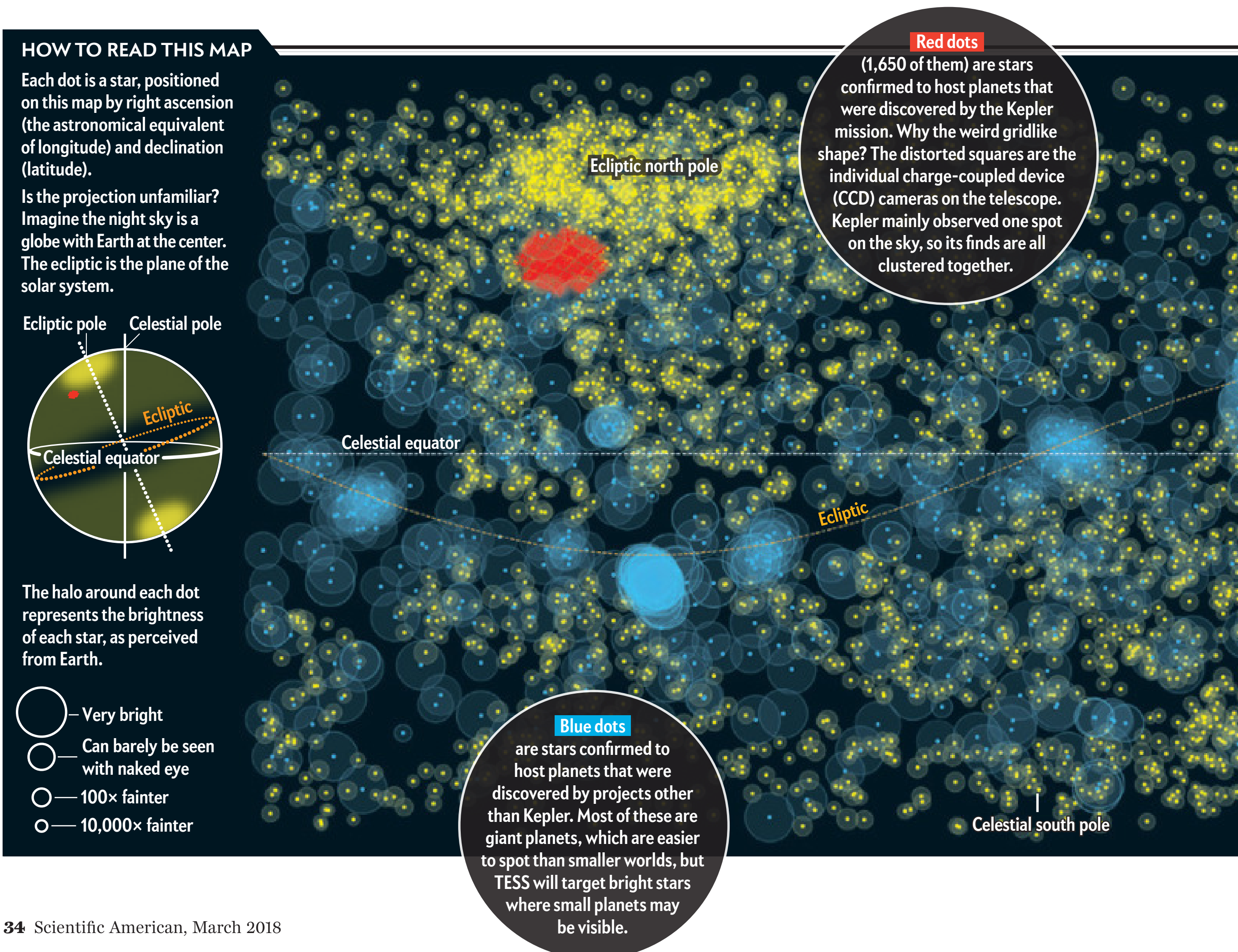
Scientists stand to add many more exoplanets to the growing tally, which should help them get closer to answering two questions: Are there other habitable worlds out there, and is there life beyond Earth in the universe?

Joshua N. Winn is an astrophysicist at Princeton University, who studies how planets form and evolve around other stars. He was a participating scientist in the NASA Kepler team and is a co-investigator for the upcoming Transiting Exoplanet Survey Satellite (TESS).

ON THE MORNING OF AUGUST 21, 2017, IN A GRASSY FIELD IN MIDVALE, IDAHO, MY FAMILY AND I WAITED WITH great anticipation. In a few minutes we would be enveloped by the moon's shadow. Along with millions of other people who had made their way to a narrow strip of land extending from Oregon to South Carolina, we were about to see a total eclipse of the sun.

Afterward I wondered how many budding young astronomers had been created at that moment, captivated by the eerie daytime twilight and the rare view of the sun's white-hot corona. Eclipses have been a source of inspiration and knowledge for centuries and still are. My own research relies not on solar eclipses but on a different type of eclipse entirely: the "transit" of an exoplanet. Although telescopes cannot actually watch a planet's silhouette move across the face of its star when that star is light-years away, the tiny dip in brightness that occurs when a planet is blocking a small portion of its star's light is enough to tell us that an alien world exists.

Astronomers detected the first exoplanetary transit in 1999. Within a decade the tally exceeded 100. Now we are up to nearly 4,000 transiting exoplanets, thanks mainly to a NASA mission called Kepler, which is due to end this year. Although the transit method is currently our most effective way of finding distant worlds, other planet-hunting techniques have turned up more than 700 exoplanets. All told, we have found a huge diversity of



worlds unanticipated by any planet-formation theories, and we suspect we are just skimming the surface of a vast ocean.

This year both NASA and the European Space Agency (ESA) are planning to launch new telescopes devoted to transiting planets. Meanwhile innovative telescopes at mountaintop observatories are extending the search to types of stars that the space missions will not explore. And all this will merely whet the appetite for the ultimate eclipse-detecting spacecraft that ESA intends to launch in 2026.

THE LANDSCAPE SO FAR

A LARGE FRACTION of what we now know about exoplanets comes from Kepler. After its launch in 2009, the telescope orbited the sun and stared unblinkingly at a patch of the sky straddling the constellations of Cygnus and Lyra, monitoring the brightness of about 150,000 stars. In 2013 the scope embarked on a modified plan following the failure of two of its reaction wheels, which keep the observatory pointed in the right direction, but amazingly it has been able to continue racking up planet finds.

This is despite the fact that eclipses are rare. Kepler found evidence for planetary eclipses in only a few percent of the stars it searched, in the form of brief and periodic decreases in brightness. Each sequence of dips betrays the existence of a planet whose orbit happens to be aligned nearly perfectly with our line of sight, causing a tiny partial eclipse each time it comes around. The fractional loss of light tells us the area of the planet's silhouette, relative to the star's cross section. Therefore, bigger bodies are much easier to detect: viewed from afar, for instance, Jupiter transiting the sun would produce a 1 percent dip, whereas the loss of light during an eclipse by Earth would be a mere 0.01 percent. No one has figured out how to measure such a minute signal with a telescope on Earth's surface; our atmosphere scrambles the starlight too much. Thus, we need space telescopes.

Kepler found nearly 5,000 candidate planets, with more than 3,500 of those so far confirmed through follow-up analysis as actual planets. Most of the Kepler planets fall into two categories: those roughly Earth-sized or a bit bigger ("super Earths") and those somewhat smaller than our eighth planet ("mini Neptunes"). The majority of planetary systems Kepler found have only one known planet, but hundreds of them have several planets, and one recently discovered system has eight, matching the solar system. These numbers reflect Kepler's own observational biases—its greater ability to more easily spot larger planets orbiting closer in to their stars—as well as the overall landscape of planets.

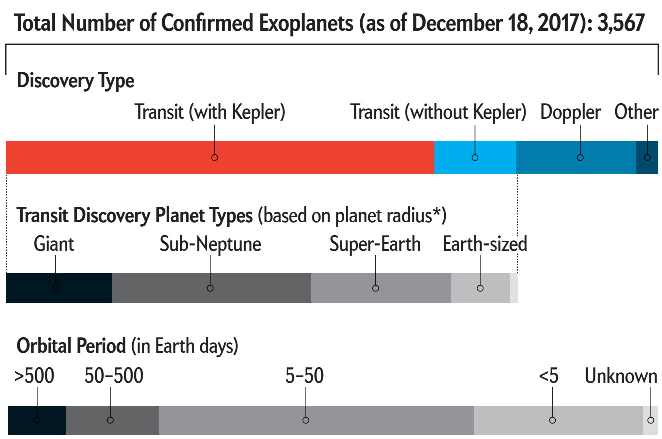
Some of Kepler's findings have been truly surprising. Its most far-reaching discovery, for instance, is in my view the existence of miniature solar systems. These have as many as six planets crowded around a star with orbits even smaller than Mercury's around the sun. What makes them so important is that they are common. If you point to a random sunlike star in the night sky, it turns out there is a 50 percent chance it has at least one plan-

NASA EXOPLANET ARCHIVE (*known host stars*); "PLANET DETECTION SIMULATIONS FOR SEVERAL POSSIBLE TESS EXTENDED MISSIONS," BY L. G. BOUMA ET AL. PREPRINT SUBMITTED TO ARXIV.ORG ON MAY 24, 2017 (*TESS targets*)

Yellow dots are simulated stars where TESS will look for planets. The simulation is based on TESS's precision, as well as scientists' understanding of the frequency of planets. The targets cluster around the ecliptic poles because those are areas of the sky where TESS will gather more data.

Exoplanet Census

Exoplanet science began to take off in the mid-1990s; since then, astronomers have compiled a catalog that now includes more than 3,500 planets orbiting other stars. Yet these are just a small fraction of the planets likely to exist out there. Most of the discoveries so far have come from NASA's Kepler telescope, which will end its mission soon. Picking up the slack will be two new space observatories, NASA's Transiting Exoplanet Survey Satellite (TESS) and the European Characterising Exoplanet Satellite (CHEOPS), both due to launch in 2018.



**We show the planet categories adopted by the TESS mission, but these categories are somewhat arbitrary, and other groups use different definitions for each planet type.*

Graphic by Jan Willem Tulp

et larger than Earth that orbits the star closer than Mercury orbits the sun. No one had foreseen that such planets would be common; in fact, some of the most detailed theories had predicted they would be especially rare. Something fundamental is missing from the standard theory of planet formation.

Kepler also found some rare and freakish planets that *had* been predicted—by science-fiction authors. One of my favorites is KOI 1843.03, an Earth-sized planet so close to its star that its dayside must be thousands of degrees. Its surface is probably covered by oceans of magma, not entirely unlike the imaginary *Star Wars* planet Mustafar, the site of Obi-Wan and Anakin's climactic lightsaber duel. The orbit of KOI 1843.03 is so tiny that it takes only 4.25 hours to make a full revolution, about the same time it takes to watch *Star Wars: Episode III* and all the bonus features. Meanwhile Kepler-16b resembles Luke Skywalker's home planet Tatooine: it has two suns in its sky. Its orbit surrounds a pair of binary stars that are themselves orbiting each other.

Then there is Kepler-36, where two planets share practically the same orbit, causing them to interact chaotically. Even if we knew the current positions of the planets to within one meter, we would not be able to predict their locations a few decades from now—it is a planetary version of the "butterfly effect." Here on Earth, the scientific revolution began with an understanding of planetary motion. Imagine how much harder that would be for any scientists in the Kepler-36 system!

Kepler was originally designed to answer the age-old question: How common, or rare, are Earth-like planets? By this term, most astronomers mean a planet of similar size and mass to Earth that could plausibly have oceans of liquid water. Such a planet must be located within the area around its star where the star's heat would be strong enough to melt water ice but not vaporize it. Scientists call this range of distances the "habitable zone" because they think that liquid water was essential for getting life started on Earth, and perhaps this is the case elsewhere.

Kepler found about a dozen potentially rocky planets in the habitable zone, bringing us right to the threshold of answering the question. Now all we need to do is divide by the number of stars that Kepler searched to calculate the percentage of stars with Earth-like planets, right? It sounds simple. In practice, the calculation is extraordinarily complex. It is not obvious how many stars that Kepler looked at were small, bright and stable enough for the telescope to have been capable of detecting Earth-like planets around them. Figuring this out will require another year or so to scrutinize the data and establish the properties of the stars.

A LARGER WINDOW

AS MUCH AS WE LOVE KEPLER, the mission had a major limitation. The telescope mainly pointed in one direction and viewed only 1/400th of the sky. As a result, Kepler had to look far away in that direction to monitor a large enough sample of stars to make the survey worthwhile. The typical Kepler star is at a distance of thousands of light-years.

Now, like any astronomer, I enjoy dazzling audiences with tales of distant objects, quadrillions of kilometers away. But from a practical perspective, far away is bad. Distant stars are faint and send only a trickle of photons to our telescopes. This faintness limits the precision of our data and renders some measurements impossible. For example, we cannot measure the masses of most of the Kepler planets. The transit signal tells us a planet's diameter but not its mass. This gap leaves us wondering what kind of planet we are dealing with. Is it dense and rocky, like Earth? Is it diffuse and gaseous, similar to Jupiter and Saturn? Or somewhere in between? Only with both the diameter and the mass can we tell.

The usual way to determine a planet's mass is to measure the star's acceleration in response to the planet's gravitational force: the more massive the planet, the more the star gets pulled around. We track the star's motion using the Doppler shift, the small shift in the wavelength of a star's light caused by its motion toward or away from us. (This method also sometimes lets us discover previously unknown planets because we can spot a star's telltale wobble even if the planet does not eclipse.) The technique requires high-resolution spectroscopy: we need to spread out the starlight into a rainbow and measure its intensity at a minimum of about 50,000 different wavelengths. For faint stars, though, there is not enough light to spread out so thinly.

NASA's next mission, the Transiting Exoplanet Survey Satellite (TESS), for which I am a co-investigator, aims to solve that problem. Onboard will be four telescopes, each 10 centimeters across, only a 10th the size of Kepler's telescope. This setup might seem strange—usually the direction of progress is toward larger telescopes, not smaller ones. But the advantage of a smaller telescope is a wider field of view; this reciprocal relation between collecting area and field of view is baked into the fundamental laws of optics. Each TESS camera sees nearly six times as much of the sky as Kepler did, and in addition TESS will rotate to peer in different celestial directions. Ultimately TESS should be able to observe many, many more bright stars than those few that happened to lie in Kepler's small field of view.

TESS is scheduled to launch between March and June of this year. For the next two years TESS will scan about 90 percent of the sky by dividing it up into 26 partially overlapping sectors and monitoring each sector for about one month. Like Kepler, we expect that TESS will discover thousands of planets, but they will be around stars that are typically 30 times brighter. This brightness will be a boon when we use ground-based telescopes to follow up on TESS discoveries—it will seem as if the light-collecting power of those telescopes had been boosted by a factor of 30 compared with their ability to follow up on Kepler finds.

And not far behind TESS is a European space mission, the Characterising Exoplanet Satellite (CHEOPS), scheduled for launch by the end of 2018. CHEOPS has a single telescope with a 32-centimeter diameter that will be used for a different and complementary mission. Whereas TESS will scan broad swaths of the sky in a methodical and predetermined pattern, CHEOPS will point at individual stars for which there is already some evidence for a planet and collect better data.

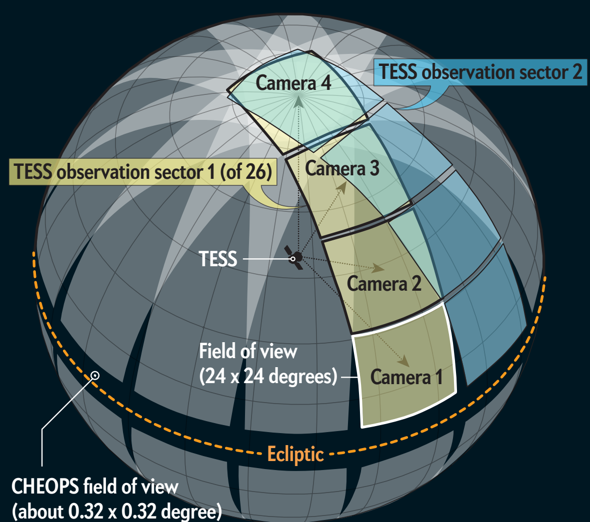
For example, TESS might find suggestive evidence for an interesting planet but with questionable statistical significance. In that case, I or one of my fellow TESS scientists will pick up the red phone hotline connecting us with the CHEOPS team to ask if they can get a better look. Or consider Proxima Centauri and Ross 128, two nearby stars for which the Doppler technique has provided evidence that Earth-mass planets are tugging them around. CHEOPS will be able to check for eclipses by these and other planets. The telescope will still require some good luck because the probability that we are viewing the orbit from the right direction is small; for Proxima Centauri, it is only 1.4 per-

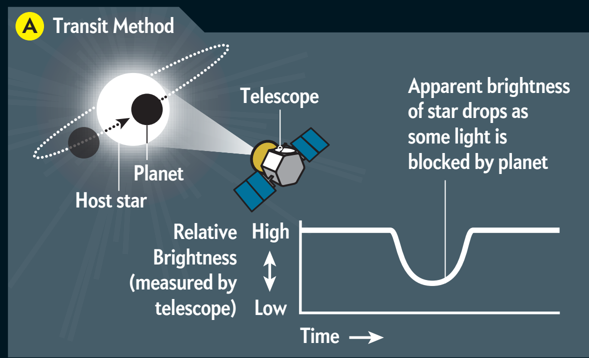
Searching for Planets

Astronomers' best tool for finding exoplanets around other stars—the Kepler Space Telescope—will soon be wrapping up its mission. In its place, two new observatories dedicated to planet hunting are due to launch in 2018: the Transiting Exoplanet Survey Satellite (TESS) and the Characterising Exoplanet Satellite (CHEOPS).

OBSERVING PLAN

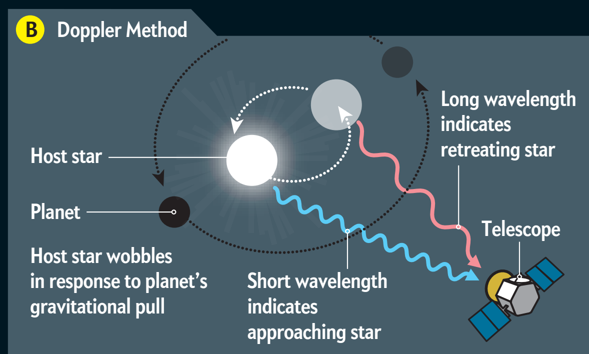
Although Kepler searches for planets in a small area of sky, TESS will be able to canvas about 90 percent of the celestial sphere. The telescope's four cameras will give it a large field of view covering 24 by 96 degrees. It will divide the sky up into 26 overlapping observation sectors and spend a month viewing each one. CHEOPS, in contrast, will study individual stars that astronomers already suspect harbor worlds to check for eclipses and to obtain better data.





HOW TO FIND PLANETS

The Kepler, TESS and CHEOPS telescopes use a technique called the transit method to identify worlds around other stars (A). When planets move in front of their star from Earth's perspective, they block a bit of starlight, causing the star to dim. Through this dimming, astronomers can identify planets that are too faint to see on their own. A second technique, the wobble method (B), looks for stars that sway instead of dim. If Doppler shifting shows that a star moves back and forth in a regular pattern, a planet's gravitational pull must be tugging the star in and out as it orbits around. This technique does not require the star and planet to be lined up from Earth's perspective, as the transit method does.



cent. But if we do hit the jackpot, we will be able to learn much more about those planets than we otherwise could.

LITTLE STARS

THESE NEW TOOLS will take us to the next frontier of planet hunting, but they still have their drawbacks. To be sure that a star's dimming is caused by a passing body, as opposed to an instrumental glitch, scientists like to see it repeat at least once and preferably many more times. TESS, however, will gaze at any given star for only one month—not nearly long enough to see multiple transits from planets such as Earth that take a year to orbit their stars. For a few percent of the sky, where all TESS's observing sectors overlap, it will look for as long as a year—but even that span is much shorter than Kepler's four-year staring contest.

As a result, TESS will largely be limited to finding planets that orbit very quickly, in a few weeks or less—not ideal. This short duration was the main compromise that scientists made to fit the mission into a $228-million budget. We decided it was a good concession because Kepler taught us that a huge variety of planets exist in short-period orbits: lava worlds, low-density "puffball" planets, chaotically interacting planets, and even planets that are apparently disintegrating in the ferocious heat of their stars. TESS will find the nearest and most easily studied examples of these types of exotic planets. A truly Earth-like planet around a sunlike star, however, will have to wait.

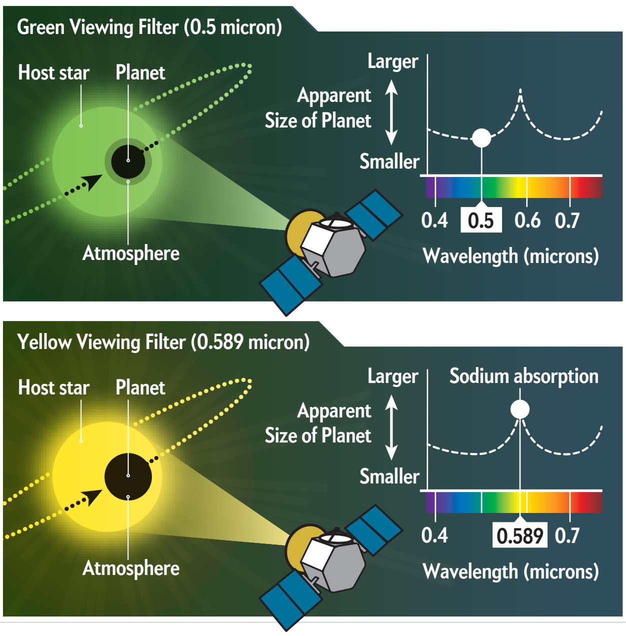
Nevertheless, TESS is an important part of the long-term quest for life on other planets. We predict that TESS will find about a dozen planets within the habitable zone, about as many as Kepler did. The trick is to stop being so insistent on a sunlike star. Astronomers like to refer to the sun as a completely ordinary star, just one of the hundreds of billions in the Milky Way galaxy. But this is a little white lie. Actually the sun is above average. Most stars in the galaxy are so-called red dwarfs, cooler and fainter stars with less than half the mass of the sun; if the sun were a spotlight on a Broadway stage, a red dwarf would be a candle.

You would need to stand awfully close to a candle to get the same warmth as you do from a spotlight. Consequently, the habitable zone of a red dwarf lies very close to the star, where the orbital periods are short. Conveniently short. For a red dwarf with a mass of a fifth that of the sun, any habitable zone planets

Illustration by Jen Christiansen

Peeking at Atmospheres

Beyond simply detecting the presence of exoplanets, transits sometimes tell scientists what their atmospheres are made of. When a planet eclipses its star, some starlight passes through the planet's atmosphere on its way to Earth. Every atom and molecule absorb and redirect specific wavelengths of light, depending on the energies of their electrons. By observing stars through colored filters and comparing which wavelengths come through when a planet is blocking the star and when it is off to the side, researchers can isolate the light signatures belonging to the planet.



would revolve around in just a few weeks, putting them within TESS's hunting ground.

Kepler looked at a few thousand red dwarfs and found that they are loaded with close-in planets, at an even higher rate than sunlike stars. Among the few hundred thousand TESS target stars are about 50,000 red dwarfs. Although they are dim, red dwarfs more than make up for it by being small, which allows planets to more easily block a large portion of their face when transiting, thereby delivering a noticeable dip in brightness to our telescopes. For instance, a planet would be equally detectable crossing in front of one star that was 16 times less bright as another star, as long as the first star had just half the radius of the second. In fact, planets in front of red dwarfs are so clear it is not even strictly necessary to use a space telescope to detect them.

For this reason, several projects are now under way at ground-based telescopes to hunt for planets around red dwarfs. Because these stars are faint, though, astronomers are using large telescopes, which will necessarily have a small field of view. They must monitor the stars one at a time, making this a low-efficiency, long-term enterprise. After years of searching, only three planetary systems have emerged from these efforts, but these three are among the most sensational discoveries in the field. One of them, TRAPPIST-1, was front-page news in early 2017. This minuscule planetary system has seven—yes, seven—Earth-sized planets packed tightly around an object of such low mass that it just barely qualifies as a star. At least two of the seven planets are in the star's habitable zone. (The name "TRAPPIST" is supposedly an acronym, but it is really one of the favorite beers of the Belgium-based principal investigator, Michaël Gillon, who has now christened a more ambitious project "SPECULOOS," after one of his favorite cookies.)

THE ROAD AHEAD

AFTER ALL THESE SPACE MISSIONS and ground-based projects, we will know the locations of thousands of transiting planets that have stars bright enough for detailed follow-up studies. We can look forward to measuring their masses, learning about planetary structure and getting more clues about the correct theory of planet formation. And if all goes well, we will have a growing collection of potentially habitable Earth-sized planets.

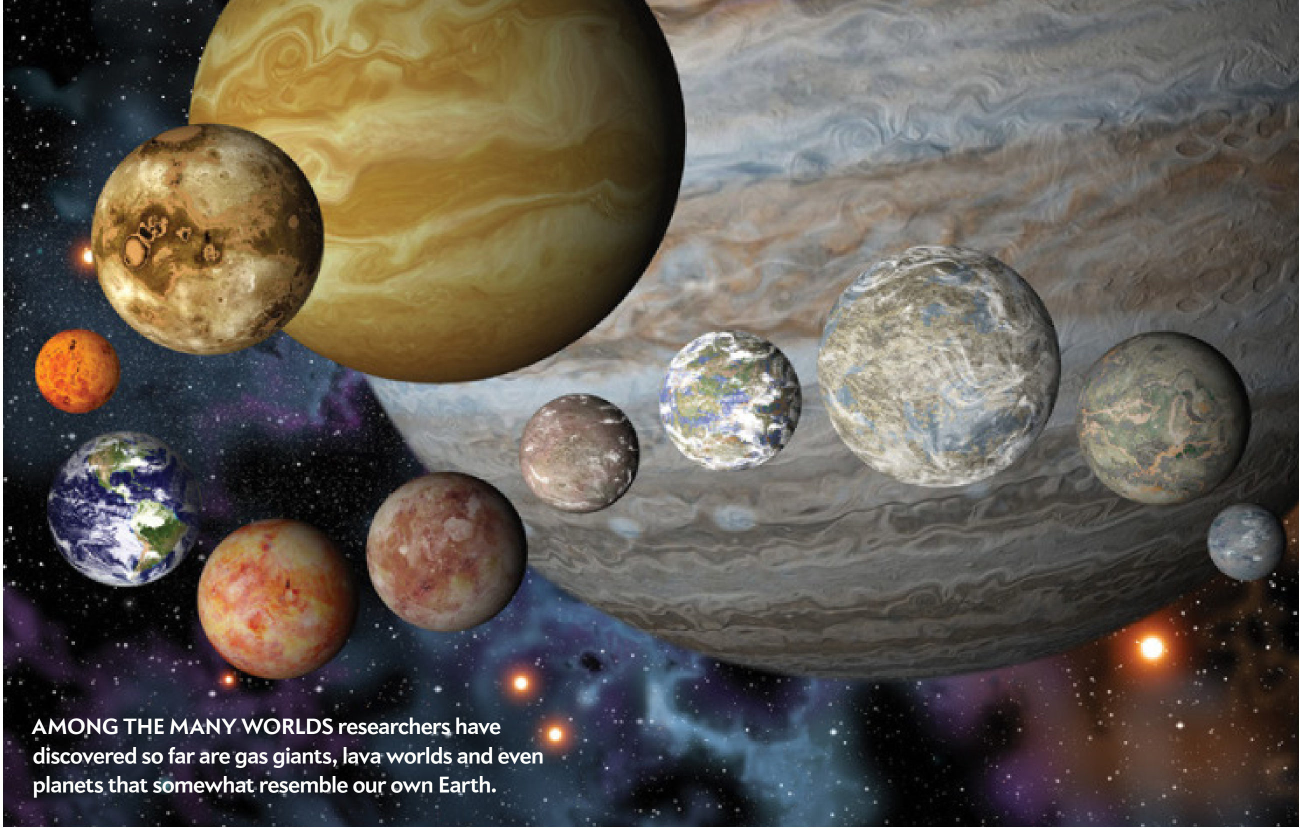
Then what? How can we take the next step and figure out if these potentially habitable planets are *inhabited?* The traditional approach, advocated since the 1950s, is to point a big radio telescope at the star and hope that we can tune in to the broadcast of any intelligent alien civilization. Though a valid plan, we have no idea if it will ever work.

Another approach is to analyze the planet's atmosphere for signs of life. We can do that by playing a transit trick. The outermost layers of a planet's atmosphere are translucent, so when the planet is in front of the star, a small portion of the starlight filters through the planet's atmosphere and makes it out the other side, where it continues on its way to our telescopes. We can then use the traditional technique of spectroscopy to probe the composition of the planet's atmosphere. Each atom or molecule has certain favorite wavelengths of light that it absorbs or deflects in other directions. This favoritism arises from the discrete set of energies that electrons have, according to quantum theory. Sodium, for instance, is fond of a particular shade of orange-yellow because the outer electron of a sodium atom can readily absorb light with a wavelength of 589 nanometers.

The trick, then, is to monitor the spectrum of the star before, during and after a transit. During the transit, the atoms and molecules in the planet's atmosphere remove starlight at their favorite wavelengths, slightly changing the observed spectrum of the star. Then after the transit is over, we see the ordinary, unaltered spectrum of the star once again. If we do this carefully enough, we can take the difference between the normal spectrum and the transit spectrum and isolate the tiny changes caused by the planet.

Astronomers have applied this technique to Jupiter-sized transiting planets and even a few Neptune- and Uranus-sized planets. It has turned up molecules such as methane, carbon monoxide and water in alien atmospheres. But we have never applied it to Earth-sized planets because their signals are so small, and the only stars we have found them around so far are too distant and faint. If we ever found oxygen in an exo-Earth atmosphere, that would get everyone's blood pumping. The reason Earth has so much oxygen in its atmosphere is because of

Illustration by Jen Christiansen



AMONG THE MANY WORLDS researchers have discovered so far are gas giants, lava worlds and even planets that somewhat resemble our own Earth.

life. If life on Earth suddenly disappeared, the rocks in Earth's crust would soak up all the oxygen to make oxides within a few million years. Thus, a planet with copious amounts of oxygen, the thinking goes, just might be home to Little Green Men—or at least some type of organism. The hope, then, is that the coming surveys will deliver Earth-sized planets around stars so bright that we will be able to interrogate their atmospheres.

In this sense, TESS, CHEOPS and SPECULOOS are acting as finderscopes for the next great observatory, the James Webb Space Telescope. This $10-billion spacecraft is scheduled to launch in 2019. Among many other things, this technological marvel will be by far the most powerful tool available for transit spectroscopy. But the Webb telescope has a planned lifetime of only five to 10 years before it runs out of the fuel it needs to maintain its orbit. This timetable creates some urgency to discover the best and brightest targets in the sky.

Because observing time on the Webb telescope will be in such high demand, some exoplanet astronomers have banded together to propose specialized space telescopes that will do nothing but transit spectroscopy. The American mission is called the Fast Infrared Exoplanet Spectroscopy Survey Explorer (FINESSE), and its European counterpart is the Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL). The word "infrared" appears in both names because molecules such as water and carbon dioxide are easiest to spot at infrared wavelengths. In the next year or two we should know whether these missions are going forward.

Even further ahead are plans for a European spacecraft called PLATO, scheduled for launch in 2026. I think of PLATO as a super-TESS that will have 24 telescopes to scan the sky, instead of just four. PLATO should be able to search for planets with greater sensitivity and over a longer duration than telescopes before it.

And at least as important is that PLATO's data quality will be high enough to detect the brightness variations associated with a star's oscillations. It turns out that stars, like any fluid body, ripple with waves that are somewhat analogous to earthquakes, which is why their investigation goes by the name "asteroseismology." The frequencies and patterns of these oscillations depend on the internal structure of a star, such as its density and composition. When PLATO finds a planet, we will benefit from a deeper knowledge of the star's basic properties, including one that is currently hidden from us: its age. As time passes, oscillations reveal age because the nuclear furnace at the center of a star converts more and more hydrogen into helium, producing subtle changes in the frequencies of waves up at the surface. Through asteroseismology we can tell whether a star has just gotten started with fusion or has been at it for 10 billion years. We will be able to see how planetary systems evolve over cosmic time.

Between scientists' ongoing analysis of Kepler data and the forthcoming TESS, CHEOPS, Webb and PLATO missions, the planet-hunting agenda is full. We are poised to finally start diving into that limitless vat we have just begun to explore. And all those budding young astronomers who were dazzled by last summer's solar eclipse will have plenty of planetary eclipses to study when they grow up. SA

MORE TO EXPLORE

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FROM OUR ARCHIVES

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CROCODILE cruises by in Gardens of the Queen, off the southern coast of Cuba.

THE BADDEST BITE

Adrenaline-fueled studies of the bite forces of crocodiles and their relatives reveal secrets of the group's evolutionary success

By Gregory M. Erickson

Gregory M. Erickson is a professor of anatomy and vertebrate paleobiology at Florida State University. He studies feeding biomechanics and growth rates in living and fossil reptiles.

ON A SCORCHING SUMMER DAY IN DARWIN, AUSTRALIA, I STOOD 10 FEET ABREAST of a 17-foot-long, 1,200-pound adult male saltwater crocodile—the world's largest reptile. It stared me down with eerie, catlike eyes, its chest heaving periodically to exhale a loud blast of spent air through its nostrils like a locomotive purging steam. Perhaps, I thought, my colleagues and I were taking our research beyond the realm of sensibility. I had worked with crocs many times before but never with such a massive one. Sweat pouring off me, I shuffled forward, armed with only a handful of electronics and a four-foot-long PVC pole capped by a device that would measure the force of the animal's bite.

I approached the crocodile from the side to within two feet of its head. Agitated, it opened its maw, displaying 64 enormous spiked teeth, and hissed—a Dantean warning not to come any closer. This was my cue. Gripping the pole, I thrust the bite-force meter into the back of the crocodile's mouth. Its jaws instantly slammed down on the device with a resounding thud, like the report of a cannon. The impact nearly wrested the meter from my hands. Then there was only silence.

I gathered my senses and took in what had just happened. The reptile was completely still, I was okay, and the equipment seemed to be intact. To my delight, the bite-force meter was perfectly sandwiched between the crocodile's back teeth. "Good bite," I called to my University of Florida colleague Kent A. Vliet, who was standing behind me holding the charge amplifier that recorded the result. "What was the force?"

"Three thousand six hundred and ninety pounds!" he replied. The research crew and a group of interested bystanders buzzed about the number while I maintained my grip on the PVC pole, waiting for the crocodile to release the meter. As my adrenaline receded, I realized that we had just recorded the highest bite force ever registered for a living animal.

That sweltering day in Australia marked the high point of a series of studies my colleagues and I have been carrying out over the past 17 years to understand the biomechanics of feeding in crocodiles, gharials, alligators and caimans—a group known as the crocodilians. Crocodilians have reigned as the undisputed apex predators in warm, near-shore freshwater and estuarine environments for more than 85 million years. Scientists have long wondered what factors have made this group so successful. Our findings not only help explain why modern crocodilians dominate these habitats today, they also elucidate how their prehistoric ancestors came to rule the water's edge in the first place.

IN BRIEF

Crocodiles and their relatives, together known as the crocodilians, have ruled near-shore environments for tens of millions of years.

Studies of the feeding biomechanics of living crocodilians have been yielding clues to their evolutionary success.

This research has implications for understanding feeding habits in other animals, including dinosaurs.

BUILT TO KILL

THE RICH FOSSIL RECORD of crocodilians shows that the shape of the body behind the head has remained largely unchanged for millions of years. Body size, however, shifted again and again, with dwarfism (lengths of less than four feet) and gigantism (lengths of more than 30 feet) evolving repeatedly. Modifications to snout and tooth shape accompanied these changes in body size. Clearly, the key to understanding a large part of the group's success lies in gleaning the form, function, performance and dietary relevance of these attributes.

As luck would have it, the 24 living crocodilian species, like their ancient predecessors, have a wide range of body sizes, from four to 23 feet. Modern crocs also show the same array of snout forms seen in fossil crocs. Scientists have already determined the diets associated with the various snout shapes of present-day crocs. Specifically, they have identified medium- and broad-snouted generalists; slender-snouted, needle-toothed forms specialized for consuming small prey, including fish; broad-snouted, bulbous-toothed forms that focus on hard prey such as mollusks; and dog-snouted, semiterrestrial feeders. Study of the feeding biomechanics of these animals in conjunction with what they eat in the wild could tell us how these remarkable predators make a living today and also open the door to understanding their past.

Back when we began our research, however, the state of the science was such that the biomechanical significance of the crocodilian snout and dentition types and body size variability was based purely on speculation

PRECEDING PAGES: BERNARD RADVANER *Getty Images*

and modeling, with virtually no empirical foundation. There were several reasons for this dearth of empirical data. Many of the world's crocodilians are highly endangered from overhunting, making them difficult for scientists to access. They are also dangerous to work with. Furthermore, the technology to determine their bite forces and tooth pressures—essential measurements for figuring out biomechanics—did not exist. This was all about to change.

In 2001 a film producer at National Geographic called me to ask whether I would be willing to determine the bite force for the extinct, 40-foot-long "supercroc" (*Sarcosuchus*), a croc relative discovered in Niger by paleontologist Paul Sereno of the University of Chicago. I replied that I could do it through bite-force experimentation on living crocodilians but that I would need to see if I could get access to specimens. I immediately contacted Vliet, who is the scientific consultant to the St. Augustine Alligator Farm Zoological Park (SAAF) in Florida—the only facility in the world that housed the 23 species of crocodilian then known—and proposed a series of studies. First, I wanted to determine the adult bite forces and tooth pressures of every extant crocodilian species using the SAAF specimens. Then I wanted to contrast captive alligator data with those from the wild using specimens acquired through local nuisance trappers and Florida Fish and Wildlife Conservation Commission biologists to see if captive values could be used to infer performance in the wild. I also intended to conduct muscle dissections and muscle-stimulation experiments on alligators to construct a model for predicting bite forces in fossil crocodilians and to use those data to understand the feeding performance of extinct crocodilians and their relatives, particularly dinosaurs. SAAF owner David Drysdale graciously gave us permission to do the testing, National Geographic provided funding for the research, and the race was on to figure out how best to collect our data before filming began.

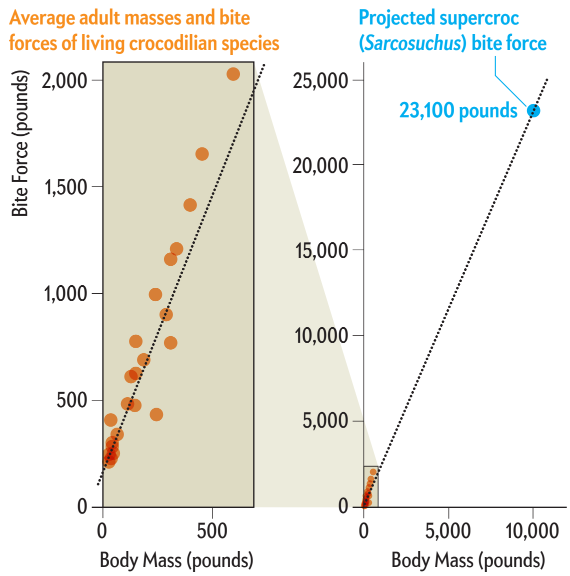
How does one measure the bite force of a crocodile? Good question. I did not know. No one had ever directly measured the bite force for any very large animal, let alone enormous, predatory reptiles. My only experience doing comparable work was testing the bite forces of tiny lizards as a graduate student using tweezerlike metal plates fitted with gauges to measure the force required to squeeze them together. To tackle this much bigger problem, I enlisted the help of an engineer I had worked with previously at Stanford University and a design engineer at Kistler, a company that makes force transducers—devices that record forces when compressed—that are used in the testing of industrial materials. Together we designed portable, water-resistant bite-force meters to use on the crocs. They look like mini bathroom scales but are much more accurate and cost up to $11,000. (I often tell my students that if they really want to know their weight, they can come by my office.) We attached a PVC pipe handle to each device and wired it to a portable charge amplifier with a readout that instantly records the output. We also padded the transducer's steel bite plates with thick layers of bull hide to mimic the feel of an actual prey animal and to protect the crocs' teeth. This turned out to be a more important measure than we had anticipated because one of my colleagues later showed that, like a person eating a jawbreaker, reptiles will not bite with full force if the material their teeth come into contact with is exceptionally hard.

After we had our technological solution in hand, the next step was to develop a protocol for testing the crocodilians. I worked with fellow crocodilian biologist Vliet and SAAF director John Brueggen to formulate a plan that would meet our research objectives while minimizing stress to our study subjects, in accordance with animal welfare guidelines. What we came up with, which miraculously worked from the get-go, entailed lassoing the crocodilians, which are unaccustomed to being handled, in their pens; dragging them out using a small army of people; securing them in place; releasing the jaws, which invariably prompts them to open; and finally, placing the meter on the rear molarlike teeth, where the bite forces are the greatest, to elicit and record a maximal-force bite. During the test, a handler on the animal's back would keep the head straight to prevent rolling. If the animal were to roll during the experiment, the results would not be a pure reflection of jaw muscle contributions to bite force, because the reptile's mass and inertia would figure into the reading. After the test, we would measure and weigh the animals. Weight is rarely recorded for large, nondomesticated animals. Nevertheless, we felt that it was important for our work because it would allow us to compare pound-for-pound bite-force performance among croc species spanning a broad range of sizes and to compare the croc data with those from other animals, regardless of body shape.

The capture and weighing process is like bull riding for scientists—although I once had a discussion with a professional bull rider who said he wanted no part of such an undertaking, noting

Chomp Champs

Crocodilian species exhibit a wide range of body sizes and snout types. Experts had predicted that species with delicate snouts would have lower bite forces and that those with stouter ones would have higher bite forces. But studies show that these animals actually all have the same impressive bite forces, pound for pound. The tight correlation between bite force and body size (*left*) has additionally allowed researchers to estimate the bite forces of fossil species, including the 40-foot-long croc relative *Sarcosuchus* (*right*).



SOURCE: "INSIGHTS INTO THE ECOLOGY AND EVOLUTIONARY SUCCESS OF CROCODILIANS REVEALED THROUGH BITE-FORCE AND TOOTH-PRESSURE EXPERIMENTATION," BY GREGORY M. ERICKSON ET AL., IN *PLOS ONE*, VOL. 7, NO. 3, ARTICLE NO. E31781; MARCH 14, 2012

Graphic by Jen Christiansen

that "bulls at least don't come back around and eat you." Similarly, I once caught and tested a 13-foot alligator with Georges St-Pierre, arguably the greatest all-time mixed martial artist, who said it was the scariest thing he had ever done and that my colleagues and I were insane. To be honest, those of us who work closely with these animals do not consider it particularly perilous. Still, the largest crocs do give us pause, and even the smaller ones can take your arm off if you do not pay attention. Like veterinarians interacting with dogs, each of us has learned how to read the crocs' behavior and handle them without causing harm to the animals or ourselves. The cardinal rules are to stay away from the pointy ends and avoid the water's edge. Crocodilians are incredibly stealthy—even 17 footers can be imperceptible in the shallows—and they can explode out of the water to ruin one's day.

We had one last piece of research protocol to figure out. Bite force is commonly seen as a reliable metric to describe a toothed animal's feeding performance. But it is only an indirect proxy. An analogy is horsepower: a 700-horsepower engine produces speed in a Ferrari but not in a dump truck. For our purposes—gauging a crocodilian's ability to successfully hunt the prey animals it encounters at the land-water interface—the most biologically relevant parameter is tooth pressure. Tooth pressure determines whether the teeth can actually penetrate food items composed of skin, cuticle, shell, bone, and so on. Pressures produced by the tooth crowns promote shear stress failure to these tissues, thereby introducing cracks or punctures that open with greater application of bite force, enabling either an immediate kill or a grip with which to drown the quarry.

To estimate tooth pressure after each bite-force test, we would place a board in the animal's jaws and tape the mouth shut. I would then reach in and make molds of the teeth with dental putty, a real-life version of the popular children's game Crocodile Dentist. The board blocks any chomps the croc might make reflexively in response to being touched on the teeth or anywhere in the mouth. But even now, after taking hundreds of molds, I still flinch at the task—putting one's hands in the mouth of a crocodile goes against all basic human instincts. Ultimately we would use the molds to make casts of the teeth in the lab and to measure the contact areas at the tooth tips. We then divided these values into the bite forces to deduce the tooth pressures.

What we learned over the course of our studies of more than 500 individuals representing all the living crocodilian species upends some of the conventional wisdom about these animals. Prior to our research, experts predicted that there would be major differences in relative bite forces among crocodilians. Those with delicate snouts and needlelike teeth that feed on softer prey such as fish would show low bite forces, whereas others that possess robust skulls and stout teeth and are capable of crushing bones and mollusks would show high values. Instead we found that all crocodilians can generate prodigious bite forces. In fact, our statistical analyses revealed that, with the exception of one species (the fish-eating gharial), they all show the same bite forces, pound for pound, regardless of whether they have hard or soft diets or are weak or strong of snout. The higher values in the range—up to 3,700 pounds—eclipse those measured or estimated for carnivorous mammals such as spotted hyenas, lions and tigers (around 1,000 pounds). We humans, for our part, can generate forces of only 200 pounds. I am often asked if one can escape from the jaws of a crocodile or alligator. Large crocodilian bite forces are equivalent to the weight of a car pressing down on the jaws. So if you can bench press a car, then you are good to go.

OPEN-AND-SHUT CASE: Author Erickson measures the bite force of an alligator.

Notably every crocodilian biologist I spoke to before we conducted this work said that wild alligators—"red in tooth and claw" and athletic from having to struggle for existence in their natural habitats—would show superior bite-force performance, compared with their often obese and lethargic captive counterparts. Instead we found that, pound for pound, they chomp with the same might. This finding was important because it showed that our data on captive animals could be used to speculate on the performance of wild individuals and that we could use those data to explore performance in fossil crocs.

From these findings, we predicted the bite force for *Sarcosuchus* and some extinct giant crocodilians. The values are around 23,100 pounds, comparable to the weight of a semi. At the other end of the spectrum, we also estimated the bite force for the smallest known crocodilian, the two-and-a-half-foot-long *Procaimanoidea,* which lived around 40 million years ago. It would have clamped down with just 141 pounds of force. My former graduate student Paul M. Gignac, now an assistant professor at Oklahoma State University Center for Health Sciences, has recently been using these data to gauge bite forces throughout crocodilian evolution.

REPTILIAN WEED TRIMMERS

OUR FINDINGS have a number of evolutionary implications. Most important, they show that throughout their 85-million-year reign as guardians of the water-land interface, crocodiles have retained the architecture of the muscles that close the jaw. The results also paint a new picture of how crocodilians repeatedly evolved the same five snout and tooth shapes and associated ecological habits. In a way, they are like weed trimmers. If one wants more force during yard work, switch to a model with a bigger engine. Crocodilians regularly achieved the same effect via the evolution of greater body sizes. To switch from cutting grass and brush to specialized applications such as edging sidewalks or sawing tree limbs, change the attachment. Crocodilians became specialized for exploiting different prey through the evolution of different jaw and tooth "attachments."

The tooth pressure data tell a complimentary story. Like the bite forces, the tooth pressures of crocodilians are unmatched by

GREGORY M. ERICKSON

any other living animal and show increases with animal size. The values range from 20,160 to 358,678 pounds per square inch (psi), dwarfing the previous record estimate of 21,321 psi for the giant fossil fish *Dunkleosteus*. Our results suggest that a secret to the catholic diets that have helped make crocodilians so successful (no croc is strictly a specialist feeder) is that any species can puncture the common food types in its realm. Different tooth forms simply allow for higher or lower pressures in more specialized feeders, which promotes greater efficiency at puncturing softer prey such as fish or sustaining impacts from hard bones or shells.

Knowing this, my students and I began to take a closer look at the factors that contribute to bite force. In 2010 Gignac examined the muscles of American alligators to develop a means of accurately predicting each muscle's contribution to the bite forces. All crocodilians have what appear at first glance to be bulging neck muscles. These are actually the so-called medial pterygoids, which are among the muscles involved in closing, or adducting, the jaw. In most animals, the medial pterygoids are small and do not add much to bite force. In crocodilians, they generate 60 percent of it.

Animals with powerful bites typically have enlarged temporalis muscles, which sit above the jaws. (These are the muscles that bulge on your temples when you clench you jaw.) Crocs, however, have beefed up their medial pterygoids, which sit under the jaws and protrude down the sides of the neck. Why? The answer has to do with how they hunt. Crocs are remarkably good at sneaking up on prey and seizing it in very shallow water at the shore. They generally approach their quarry with very little of their head protruding from the water aside from their nostrils for breathing, eyes for seeing and ears for hearing. The rest of the giant body remains submerged until the predator lunges at the unsuspecting prey. Crocs are stealthier with their jaw adductors hidden below the water line than they would be if they had instead built up the much more prominently located temporalis. Like submarines at periscope depth, crocs have only the requisite sensing equipment above the water—everything else is down below.

Gignac's analyses of the muscles involved in croc bite force shed light on another puzzle as well. In our initial tests, the slender-snouted, needle-toothed, fish-eating gharial showed aberrant bite-force generation. Its forces fall some 50 percent below the croc norm. When Gignac dissected one of the animals, he found that its medial pterygoids are relatively small, but its upper jaw-closing muscles are large for a crocodilian. That arrangement favors speed of jaw closure over bite force. We suspect that the gharial, being the most piscivorous croc species, sacrificed bite force for more rapid seizure of fish.

This line of research resolves another croc conundrum. During our testing of the giant Australian saltwater crocodile, the animal held onto the bite meter for 10 minutes before releasing it. We discovered that movement of the meter in this situation elicits clenching bites of nearly the same magnitude as the initial full-force bite. I have personally recorded up to 22 of these clenching events and sometimes have waited 25 minutes to recover the equipment—you get the meter back when the crocodile wants to give it back, never earlier. That fact left us wondering about the significance of this behavior and how it was generated.

To find out, we hooked a computer up to our bite meter and recorded the forces throughout bite-force experimentation on wild American alligators. This sequence showed that the holding forces were roughly 10 percent of the maximal bite forces. We posit that this hardwired behavior is related to how gators drown large prey. In the wild, alligators typically use an aggressive bite to puncture game and gain a purchase with their teeth. They then take the food item to deeper water and drown it. If the prey struggles, the alligators reengage the teeth with full-force biting. Gignac's dissections revealed that these holding and clinching abilities come from a remarkable physiological specialization of the muscles. He noticed that the massive jaw-closing muscles that generate most of the maximal bite forces are white in color, analogous to the turkey breast muscles that can generate short bursts of force for flight but tire easily from a lack of a blood supply. He then discovered red and pink oxidative muscles for sustaining the low force-holding behavior. They are akin to the dark meat found in turkey legs, which are highly vascularized and rich in myoglobin for sustained walking. Gignac's model shows that together, these previously unrecognized dark muscles generate 10 percent of the alligator's bite force, just enough to keep the teeth engaged.

T. REX BITES AGAIN

OUR WORK HAS APPLICATIONS for understanding feeding in animals beyond crocodilians. Gignac and I have since used the data to develop the first viable bite-force model for *Tyrannosaurus rex*. Previous estimates of *T. rex*'s bite force used models based variously on alligators, lizards and even mammals. Needless to say, the results were disparate, ranging from 18,000 to 245,000 pounds. In contrast, our model, which is specific to archosaurs—the group that comprises crocodilians, birds and their extinct relatives—yielded a value of around 8,000 pounds. That is twice what the largest living crocodilians are capable of. Moreover, *T. rex*'s tooth pressure—431,342 psi—is the highest pressure estimated for any animal. Based on these new estimates, which we published in 2017, we solved the mystery surrounding how, as fossil evidence indicates, the king of dinosaurs could pulverize the bones of its prey. Today only carnivorous mammals with upper and lower teeth that come into full contact, or occlusion, during chewing can manage this feat.

Crocs are magnificent predators, and we have made great progress in figuring how they got that way, but many questions remain unanswered. It is likely, for example, that snout shapes could affect bite force underwater in ways that they do not on land. That means we need to repeat our tests underwater. It is easier said than done: doing so requires that we develop new bite-force meters that work when fully submerged and partner with engineers to understand how water flow might affect jaw-closing velocity and bite force. Moreover, we need to develop new safety protocols: crocs have the upper hand in the aquatic realm. We'll get there. We may be more gray-haired and banged up than we were when we started this research, but we are up to the task. SA

MORE TO EXPLORE

Insights into the Ecology and Evolutionary Success of Crocodilians Revealed through Bite-Force and Tooth-Pressure Experimentation. Gregory M. Erickson et al. in *PLOS ONE,* Vol. 7, No. 3, Article No. e31781; March 14, 2012.

The Biomechanics behind Extreme Osteophagy in *Tyrannosaurus rex*. Paul M. Gignac and Gregory M. Erickson in *Scientific Reports,* Vol. 7, Article No. 2012; May 17, 2017.

FROM OUR ARCHIVES

Breathing Life into *Tyrannosaurus rex*. Gregory M. Erickson; September 1999.

scientificamerican.com/magazine/sa

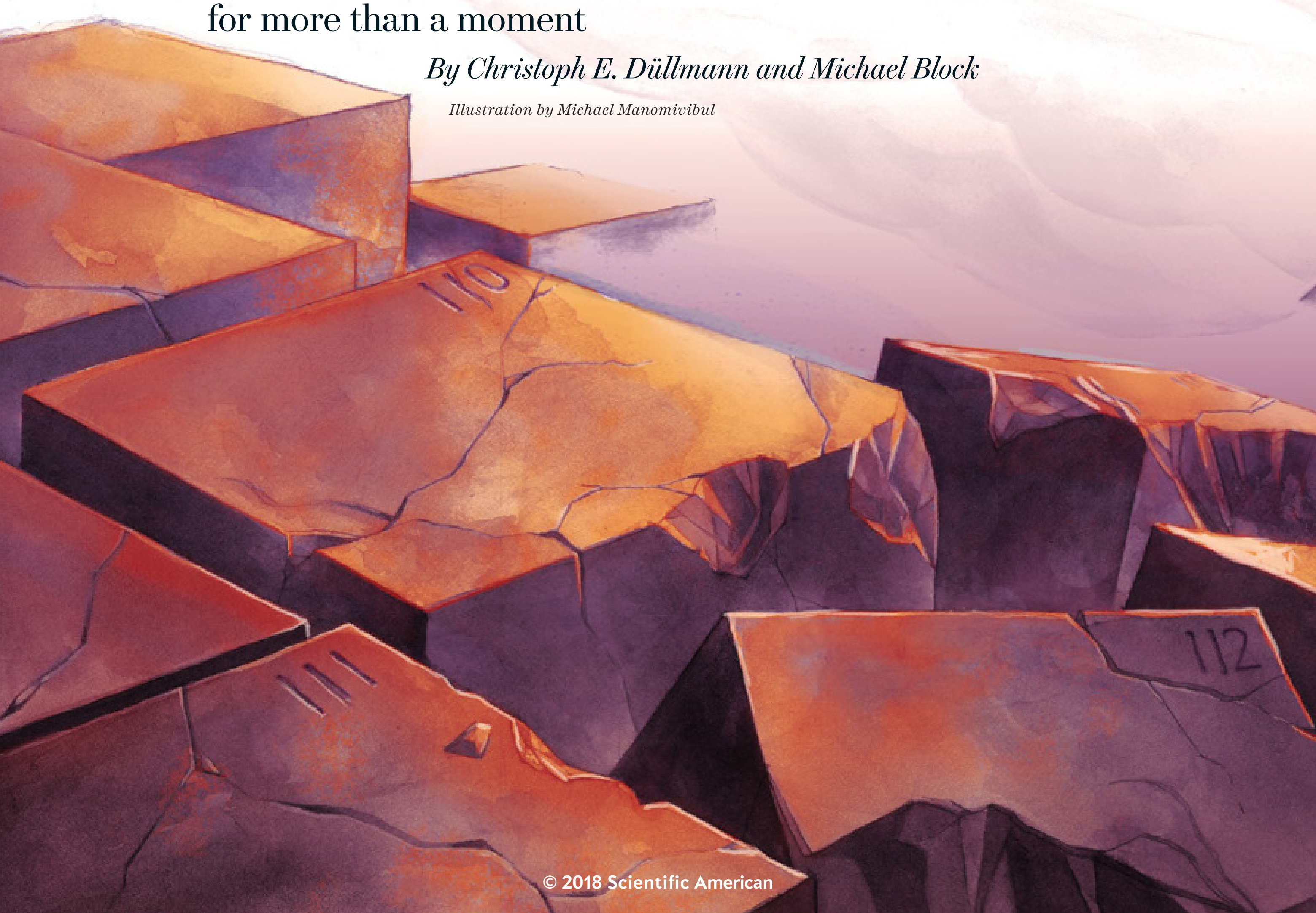
CHEMISTRY

ISLAND OF HEAVYWEIGHTS

A race is on to create the world's heaviest elements—and to explore the periodic table's "island of stability," where these elements exist for more than a moment

By Christoph E. Düllmann and Michael Block

Illustration by Michael Manomivibul



Christoph E. Düllmann is a nuclear chemist at Johannes Gutenberg University Mainz, the GSI Helmholtz Center for Heavy Ion Research in Darmstadt and the Helmholtz Institute Mainz, all in Germany. He studies the synthesis and nuclear and chemical properties of superheavy elements and their compounds.

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THE HEAVIEST ELEMENT THAT HUMANS HAVE EVER FOUND IS CALLED OGANESSON. EACH ATOM OF THE stuff packs a whopping 118 protons into its dense center. In contrast, hydrogen—the most abundant element in the universe, something you can find in your body, Earth's oceans and even the atmosphere of Jupiter—has only one. Scientists announced the discovery of oganesson in 2006, when a Russian-American team used a particle accelerator in Dubna, Russia, to fire millions of trillions of calcium ions at a target of heavy atoms. After 1,080 hours of collisions, the investigators had created three atoms of this new superheavy substance.

A few milliseconds later they were gone.

But by carefully accounting for all of the radiation and smaller atoms that the reactions produced, the scientists at the Joint Institute for Nuclear Research in Russia could be fairly sure that they had, for a brief sliver of a moment, created the element. In 2015, after more than a decade of vetting and rechecking, element 118 officially joined the periodic table of the elements, the world's master list of matter. It was named for Yuri Oganessian of the Russian-based institute, who is a pioneer of this research.

But how many more elements are out there? In just the past decade scientists have been pushing the periodic table further and further, adding new atoms that are heavier than ever before. Each one of the fundamental bits of nature on the table is defined by the number of protons packed in its atomic nucleus. At the same time that oganesson became official, researchers also added elements containing 113, 115 and 117 protons per atom to the periodic table. One of us (Düllmann) has been conducting some of the first chemistry experiments on several of the so-called superheavy elements, and Block has been working on the first direct mass measurements and other investigations into some of them. Each new species we find is exciting because it represents an unknown material, a form of matter humans have never encountered before.

We cannot keep them, however. The few atoms we make exist only for brief moments before collapsing or transforming under the strain of too many positively charged protons repelling one another. But scientists suspect that certain yet to be discovered superheavy elements and isotopes (versions of the same element

IN BRIEF

Scientists are trying to create heavier and heavier elements by forging atoms with more and more protons in their nuclei.

Most of these "superheavy" elements are extremely short-lived, but theory predicts that if scientists can create atoms with the right combinations of protons and neutrons, they might become stable and endure for minutes, days or even years.

Such atoms would form an "island of stability" on the periodic table of the elements. Researchers think that some recently discovered atoms might represent the shores of this island.

Periodic Table of Elements

Chemistry's essential chart arranges all the known elements according to the number of protons found inside their atoms' nuclei. Scientists are trying to expand the table by discovering heavier elements with more and more protons. They must coax "superheavy" elements (*shown in pink*) into being in laboratory experiments because they are too unstable to exist in nature and many tend to decay very soon after they form.

Atomic number (number of protons found in the nucleus of the atom)

H 1																	He 2
Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
Cs 55	Ba 56	* 57–71	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
Fr 87	Ra 88	** 89–103	Rf 104	Db 105	Sg 106	Bh 107	Hs 108	Mt 109	Ds 110	Rg 111	Cn 112	Nh 113	Fl 114	Mc 115	Lv 116	Ts 117	Og 118
119	120																

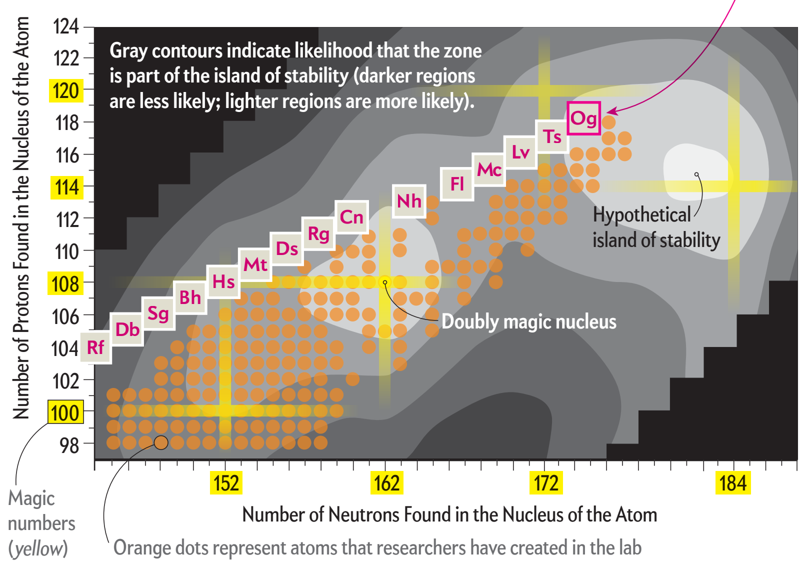
Hypothetical positions of the yet unknown elements 119 and 120

Lanthanides(*) and actinides (**) are grouped together off the main body of the table because of their similar chemical properties

*	La 57	Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
**	Ac 89	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103

Island of Stability

Because each proton in a nucleus adds positive charge that repels the other protons, the more of these particles, the more likely the nucleus is to break down. Yet scientists think some undiscovered atoms might buck this trend by becoming stable through special arrangements of protons and neutrons, which are thought to occupy "shells" inside nuclei that each hold a specific number of particles. A shell is most stable when it is completely full, so the numbers of protons and neutrons it takes to fill a shell are called magic numbers. Intriguingly, some numbers are more likely to be magic in combination with certain other numbers. Theory suggests, for example, that 114 protons and 184 neutrons might be magic numbers together (a "doubly magic" nucleus), but scientists have not yet created an atom with this combination. If they could, it might form part of an "island of stability," where superheavy elements become long-lived.



with different numbers of neutrons) might break this teasing pattern of fleeting, tantalizing existence. Some of our envisioned elements may linger for minutes, maybe even years without decaying. If so, they would form a long-sought region on the periodic table called the island of stability. Thanks to special configurations inside their nuclei that grant unusual stability, superheavy elements inhabiting this region may not be just ephemeral creations of the laboratory but could actually stick around. Lately scientists are finding atoms that may represent the shores of this island.

Element 114, for instance, decays somewhat less quickly than some calculations had predicted that an atom jammed with that many protons must. And the half-lives of some of the recently discovered superheavy elements—that is, the time it takes for half of the atoms to decay into another element—get successively longer (although they are still very brief) as their number of

SOURCE: CHRISTOPH E. DÜLLMANN

Graphic by Jen Christiansen

neutrons (the chargeless companions of protons in atomic nuclei) increases. These observations fit with predictions—the island is traditionally conjectured to lie in an area of the periodic table where atoms have somewhere around 114 protons and more neutrons than any species created so far. But the discovery of these slightly extended life spans—just a fraction of a fraction of a fraction of a second more—has invigorated a quest that has been a driving force for several generations of heavy element researchers. Now that we have begun to explore the island of stability, we hope to chart its boundaries, determine the location of its heart—where the most stable isotopes lie—and discover how long these atoms can linger.

In recent years scientists have gleaned fascinating insights about these strange denizens of the extreme reaches of the periodic table. Our lab techniques have developed to the point that we can study the chemistry of the superheavy elements we create and determine, for example, whether they would be metals or gases at room temperature. And if we could ever create a kilogram of them, these elements might have completely new—and potentially useful—properties that would distinguish them from all the known materials. Even if the substances we make persist in decaying much too soon for us to ever hold some in our hands, they can help us gain a deeper understanding of chemistry and the fundamental nature of matter.

Now that we have begun to explore the island of stability, we hope to chart its boundaries, determine the location of its heart—where the most stable isotopes lie—and discover how long these atoms can linger.

EXPLORING THE ISLAND

THE PERIODIC TABLE is chemistry's ongoing attempt to map that fundamental nature. The chart was developed in the 19th century, most clearly by chemist Dmitri Mendeleev and independently by chemist Julius Lothar Meyer. It lists elements in the order of their atomic number (the number of protons per atom) and lines them up to show similarities in the ways they react with atoms of other elements to form chemical compounds.

Almost as soon as the table was first formulated, chemists wondered how far it extended. The heaviest element found in large quantities in nature is uranium, whose nuclei contain 92 protons. But with each additional proton inside a nucleus, the positive charge grows—and so does something known as the Coulomb force, which repels like charges away from one another. At some point, this push becomes stronger than the attractive "strong interaction" that binds atomic nuclei together, and the nucleus splits apart in a process called fission.

But the stability of any particular element comes down to more than just the number of protons it holds—it depends on the arrangement of protons and neutrons within the atomic nucleus. According to the nuclear shell model developed by Nobel laureates Maria Goeppert Mayer and J. Hans D. Jensen in the late 1940s, both constituent particles fill so-called nuclear shells. Akin to layers within nuclei that can hold specific numbers of protons and neutrons, they are analogous to the electron shells that hold electrons around the nucleus. In both cases, full shells lead to stronger binding, providing extra stability.

Scientists conceived of the shell model when they realized that for specific "magic" numbers of protons and neutrons (2, 8, 20, 28, 50 and 82) nuclei are more stable and harder to rip apart. These magic numbers, it became clear, correspond to full shells. The magic numbers for protons and neutrons in the atoms we know are the same, but there is no guarantee they will continue to match. A nucleus where both proton and neutron shells are full is called doubly magic.

There is much we still do not understand about magic numbers. For instance, what are the magic numbers for nuclei that we have not yet discovered? Some theoretical predictions forecast a doubly magic superheavy nucleus with 114 protons and 184 neutrons. Although we have created element 114 in labs, we have not made a version with 184 neutrons. Yet the prediction of this magic combination, first made in the 1960s, suggested that such an isotope would be so remarkably stable that it would have a half-life approaching the age of Earth. This prediction was the first suggestion of the island of stability—a notion that ignited the field with excitement then and continues to drive us.

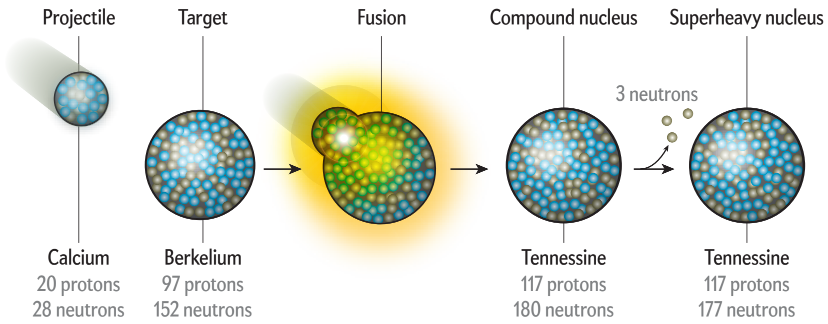
We still do not know, however, if 114 and 184 are a true magic combination. Other theoretical frameworks predict, for instance, configurations such as 120 or 126 protons and 172 neutrons. Some of our predictions of future magic numbers owe a debt to Albert Einstein. He explained the surprising observation that the mass of an atom is smaller than the sum of the masses of its constituent protons, neutrons and electrons. His famous formula $E = mc^2$ states that this mass defect reflects the binding energy—the ener-

gy that holds the nucleus together. Weighing atoms with different compositions of protons and neutrons thus allows us to identify those configurations that result in a stronger binding—in other words, configurations that represent magic numbers—and to determine how much more stable they are.

Whatever the next magic numbers turn out to be, we think we are starting to encounter the island of stability. Experiments have found that the half-lives of superheavy elements increase with the amount of neutrons, suggesting we are approaching the next magic number of neutrons. This trend is nicely displayed, for example, in the case of element 112 (copernicium, or Cn): compared with Cn 277 (copernicium with 112 protons and 165 neutrons), which lives for only about 0.6 millisecond, Cn 285 (copernicium with eight more neutrons, for a total of 173 neutrons) lives for about 50,000 times longer. The pattern most likely will continue toward the center of the island of stability, although whether any superheavy elements exist that are stable indefinitely is still an open question.

Creating Superheavy Elements

To make a new superheavy element, scientists accelerate a "projectile" nucleus into a "target" nucleus and hope the two combine. To overcome the repellent force between the two positively charged nuclei, the projectile must be going about 10 percent of the speed of light. At this velocity, the projectile and the target can come close enough to practically touch, and here the attractive pull of the strong nuclear force kicks in. In the example shown, scientists created the element tennessine by fusing calcium and berkelium. After the two joined, the "compound nucleus" evaporated three neutrons to create the superheavy nucleus of tennessine with 117 protons and 177 neutrons.



The possibility, though, has triggered a search for these elements in nature. Just because we have not seen them in large quantities, the reasoning goes, does not mean that trace stores of them are not hiding in plain sight. They could have been formed along with other elements heavier than iron in powerful events such as the collision of two dense stars called neutron stars and then seeded throughout the universe. In that case, they could be present in cosmic rays beaming toward us from space or could have survived within rocks on Earth. Scientists have made many searches using different techniques. For instance, element 110 (darmstadtium) is predicted to be quite stable when it has 184 neutrons—a magic number—and might be expected to be chemically similar to platinum, which lies directly above it on the periodic table. Scientists used techniques such as x-ray fluorescence and mass spectrometry to search for the presence of darmstadtium in naturally occurring platinum ores but found no evidence for it in amounts greater than one part in 10^9.

Researchers have also looked for signs of superheavy elements in cosmic rays—for example, using the Ultra-Heavy Cosmic-Ray Experiment onboard NASA's Long Duration Exposure Facility—but they have found no conclusive evidence. Efforts will certainly continue because such a discovery would be hugely significant. Moreover, new elements could translate to novel materials, each with unique properties that might be useful for technology and other applications.

FORGING NEW ELEMENTS

BECAUSE WE HAVE NOT yet found any superheavy elements in nature, we must create them ourselves in labs. The task at hand is to enrich the atomic nuclei of "common" elements with even more protons. Up to a point, we can do so by mimicking the process the universe uses to form heavy elements. Nuclei containing too many neutrons are prone to transforming one of their extra neutrons into a proton in the so-called beta decay process, which then produces an element heavier by one atomic number. We can form elements up to fermium (element 100) by bombarding heavy elements with more neutrons. Thus far, though, no fermium nuclei or heavier ones are known to undergo the corresponding beta transformation process, so this pathway ends there.

To go beyond, to create elements such as the elusive oganesson, scientists can bring two nuclei into close enough contact that the strong force kicks in. This force has an extremely short range, meaning that the nuclei must almost touch one another to feel it. To get that close, we have to overcome the repelling force of the positively charged protons, meaning that we must accelerate one of the nuclei to about 10 percent of the speed of light and shoot it at the other. This velocity is just about sufficient to overcome the Coulomb repulsion, whereby the two nuclei make surface contact with each other. But the probability for the two nuclei to touch is extremely small. Furthermore, merging the two initial nuclei into a single combined nucleus gets ever more unlikely the more protons the system contains. Even if such an amalgamated "compound nucle-

Graphic by Jen Christiansen

us" does form, it often splits back into lighter fragments practically immediately. Both tendencies—the small probability for a compound nucleus to form in the first place and the large probability for it to split once it is formed—play strongly against the synthesis of ever heavier elements.

Despite the challenges, researchers have achieved exciting successes using this approach. Elements 113, 115, 117 and 118, all made following this pathway, received their official names in 2016. (The International Union of Pure and Applied Chemistry, or IUPAC, is chemistry's version of Guinness World Records and has the power to officially recognize and name new elements.) Element 113 is now called nihonium, honoring Japan, where the experiments to synthesize this element took place. Element 115 is moscovium, honoring the Moscow region, home of the Joint Institute for Nuclear Research, where this element was discovered. And 117 was dubbed tennessine after the state of Tennessee, where Oak Ridge National Laboratory provided the target nuclei of element 97 (berkelium) needed to synthesize the new substance. Oganesson, with its 118 protons, rounds out the new inductees.

Now the heat is on to find element 119, which would add a whole new row to the periodic table. Although several groups, including our own, have gone after these higher numbers, none has succeeded to date, despite investing weeks and months at the world's most powerful accelerators. One obstacle is that the successful route employed up to oganesson—smashing calcium atoms into heavier nuclei—comes to an end at 118 because we do not have sufficient amounts of nuclei with more than 98 protons to use as targets. Scientists are now trying to identify which combinations of known and available elements provide the best chances to generate new species.

Even if these new species decay in a flash, scientists have recently made breakthroughs in their ability to perform experiments during the brief time the elements last to learn about their chemistry.

STRANGE CHEMISTRY

EVEN IF THESE NEW SPECIES decay in a flash, scientists have recently made breakthroughs in their ability to perform experiments during the brief time the elements last to learn about their chemistry and properties—such as whether they behave more like metals or gases at room temperature.

The heaviest element whose chemical properties researchers have studied is flerovium (element 114, or Fl). Flerovium's position on the periodic table, below lead, implies it should be a typical heavy metal. But theories dating back to 1975 suggest it might actually behave more like a noble gas—a very inert gas that rarely interacts with other materials.

The odd expected behavior of flerovium all comes down to how many protons its nuclei contain and, therefore, how highly charged they are. The extreme positive charge of heavy elements' nuclei accelerates their negatively charged electrons to velocities that can reach 80 percent of the speed of light and thereby cause them to revolve around those nuclei in different orbital shapes that have variable spacing than those of the smaller elements. For flerovium, for example, there is a much wider gap in the energy levels of its two outermost electron orbitals than in similar smaller nuclei, such as lead, which sits just above flerovium on the periodic table. In lead's case, forming a chemical bond will more easily provide the energy electrons need to overcome this gap than it will for flerovium. Consequently, flerovium might not undergo chemical reactions as readily as its lighter counterpart. It may therefore resemble other elements that do not like to undergo chemical reactions—the noble gases—more than typical metals such as lead.

It is hard to predict, though, exactly how flerovium will behave. Theories generally agree that it should be more inert than lead, but it is probably more reactive than true noble gases and could form, for example, weak metallic bonds with elements such as gold. Because we have not been able to create it in large enough quantities to observe with human eyes, no one knows what this element would look like in bulk. Some predictions suggest it might appear silvery white or pale gray and take solid form at room temperature.

Flerovium's intriguing properties have inspired scientists to go to extreme lengths to experiment on it, despite the fact that we can produce just single atoms of the stuff per day. Further, even the most long-lived known Fl isotopes have half-lives of only one to two seconds. One of the best facilities we have for producing flerovium is the TransActinide Separator and Chemistry Apparatus (TASCA) at the GSI Helmholtz Center for Heavy Ion Research in Germany. There we shoot a beam of calcium 48 toward a rotating target wheel covered with plutonium 244. When flerovium atoms result, magnets steer them toward a system called the Cryo-Online Multidetector for Physics and

Chemistry of Transactinides (COMPACT). This machine consists of two sets of 32-centimeter-long arrays of silicon detectors facing each other, separated by about half a millimeter and forming a narrow, rectangular channel, where a rapidly flowing gas forces flerovium through. The detectors are covered with a very thin gold layer, which allows us to study how the flerovium atoms interact with this metal. The first detector channel is kept at room temperature, but the end of the second channel is cooled with liquid nitrogen to below –160 degrees Celsius because weak bonds—like those exhibited by noble gases—will only be strong enough to bind flerovium atoms at low temperatures but not under warmer circumstances. If flerovium acts more like a metal than a noble gas, it will adsorb on gold on first contact at the warmer beginning of the channel. But noble gases interact too weakly with gold to remain bound at room temperature, so if flerovium behaves more like a noble gas, it will bond in the later part of the channel, if at all.

When our research group used this setup, we observed two atoms that both decayed in the room-temperature detectors, suggesting that flerovium bonded, and then decayed, quickly, more like a metal than a noble gas. Another earlier experiment, though, run by a group at the Paul Scherrer Institute in Switzerland and carried out at the Flerov Laboratory of Nuclear Reactions in Russia, observed three atoms. Although one decayed in the early part of the channel, the two others were found at low temperatures around –90 degrees C. The experimenters interpreted this result as hinting at behavior more like a noble gas. We are currently analyzing data obtained just recently at GSI that we hope will clarify the properties of this exciting element.

SUPERHEAVY BREAKTHROUGHS

RECENTLY one of us (Block) and his team conducted the first laser spectroscopy experiments on a superheavy element—nobelium, or element 102. They were able to produce nobelium atoms at a rate of a few particles per second by bombarding calcium atoms (20 protons) at a target of lead (82 protons). Block and his colleagues then slowed down the resulting nobelium atoms in an argon gas and shot laser pulses at them. If the laser pulses were of the right energy, a nobelium electron would absorb the laser energy and escape from the atom. By varying the frequency of the laser pulses, they were able to precisely measure the energy needed to remove an electron from the nobelium atom. This "ionization energy" is one of the characteristic properties of an element that affects its placement on the periodic table. It determines how likely the element is to react with other elements and form chemical bonds.

We first performed these studies on the isotope No 254 (a version of nobelium with 152 neutrons) and recently extended the experiments to two additional nobelium isotopes, No 252 and No 253, to learn how the different neutron contents shift the energies that the atoms' electrons are able to absorb. The results will tell us about how the size and shape of the nuclei of these isotopes vary—different configurations of the positively charged nuclei will affect the way the negatively charged electrons orbit and behave.

Scientists have also been creating chemical bonds between superheavy elements and more modest atoms to study how the exotic species interact. A recent example is the synthesis of molecules containing seaborgium (element 106). In experiments conducted at the RIKEN Nishina Center for Accelerator Based Science in Japan, Düllmann's group led a team that produced atoms of an isotope of seaborgium with a half-life of about 10 seconds. The scientists then added carbon monoxide to the chamber containing the seaborgium and discovered that the heavy element transformed into a hexacarbonyl compound in which six carbon monoxide molecules bound to the central seaborgium atom.

Düllmann and his colleagues found that in this situation, seaborgium acts much like its lighter and more familiar homologues tungsten and molybdenum, which have the same number of valence electrons. In an approximately two-week-long round-the-clock experiment with seaborgium, the researchers observed seaborgium forming the same type of compound with carbon monoxide molecules as molybdenum and tungsten do, at similar rates. Scientists are now moving to test which of the three elements forms the most stable bonds with carbon monoxide—calculations performed in the late 1990s suggest it will be seaborgium, but more recent and advanced calculations predict the carbon monoxide bond with seaborgium will be weaker than the bond with tungsten.

These are just a few examples of the type of fascinating experiments currently going on with superheavy elements and the many open questions we hope to answer. Although these newest members of the periodic table are admittedly quite exotic, experimental studies provide ever more direct information on how they fit into the same elemental system established by the more common elements that we encounter in our daily life. Whether they be unstable or long-lived—indeed, whether we ever find the heart of the island of stability—superheavy elements have much to teach us about the workings of nature's chemical building blocks. SA

MORE TO EXPLORE

Special Issue on Superheavy Elements. Edited by Christoph E. Düllmann, Rolf-Dietmar Herzberg, Witold Nazarewicz and Yuri Oganessian. Special issue of *Nuclear Physics A,* Vol. 944; December 2015.

Superheavy Elements (SHE) Chemistry group at Johannes Gutenberg University Mainz, the GSI Helmholtz Center for Heavy Ion Research and the Helmholtz Institute Mainz: **www.superheavies.de**

Publications for the Separator for Heavy Ion Reaction Products (SHIP) at GSI: **www.gsi.de/work/forschung/nustarenna/nustarenna_divisions/she_physik/publications.htm**

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scientificamerican.com/magazine/sa


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NEUROSCIENCE

A Look Within

Imaging technologies could find the best treatments for depression and addiction—and could even reshape education

By John Gabrieli

Illustration by Amy Martin

John Gabrieli is director of the Athinoula A. Martinos Imaging Center at the McGovern Institute for Brain Research at the Massachusetts Institute of Technology. He also holds the Grover Hermann Professorship at the Harvard-M.I.T. Program of Health Sciences and Technology.

EVERY DAY PEOPLE WITH COMMON MENTAL HEALTH DIFFICULTIES receive prescriptions for therapies that will not help them. Finding treatments that work for these patients entails an arduous process of trial and error. Each failed therapy risks leaving a patient despondent about whether anything will ever help.

Depression illustrates poignantly what can go wrong. By most measures, half to two thirds of patients diagnosed with depression will fail to benefit from any particular treatment. Research protocols for depression consist of clinical trials that typically evaluate the general effectiveness of a drug or behavioral therapy based on the *average* benefit for a patient. They overlook, however, the wide range of individual patient outcomes, ranging from full recovery to no benefit at all. The largest and longest evaluation of drug treatment for depression, a National Institutes of Health study of thousands of patients at multiple U.S. health care institutions called STAR*D, illustrates what can happen. Every patient in the study received an initial drug, and about a third showed major improvements. Only about a quarter of those who failed to respond to the first drug benefited from the second. After a third and fourth prescription for other drugs, 70 percent of patients demonstrated substantial progress. But most had to experience one or more treatment failures before finding a drug that worked.

Failed treatments not only prolong distress, they also discourage patients from seeking help. Participants in STAR*D knew they had possible access to other treatments in the next phase of the study, but even so many gave up. A substantial number of patients dropped out of the study after an initial failed pharmaceutical treatment, about 30 percent after a second therapy and about 42 percent following a third. (Behavioral treatment of depression using the form of talk therapy known as cognitive-behavioral therapy, or CBT, also yields a strong benefit for about half of patients.)

Explanations for the difficulties psychiatrists face relate to the imprecisions and economic imperatives of drug development. Two people diagnosed with the same mental health disorder can respond in wholly different ways to the same drug treatment because of the current inability to assess who will respond to which treatment. Yet pharmaceutical companies typically aim for the largest possible market rather than tailoring treatment to smaller patient groups that exhibit a specific form of depression or another psychiatric disorder. Drug developers also lack the tools to implement a more precise approach. Diagnostic techniques to predict whether a person will profit from a given treatment are not part of routine medical practice.

In recent years various brain-imaging techniques, combined with sophisticated algorithms that analyze neural activity, have started to reveal brain differences among people that predict whether a given drug or talk therapy will lift a patient out of a depression or relieve severe social anxiety. Early versions of these diagnostic techniques have also shown promise in determining whether an alcoholic might relapse—and they have even begun to identify whether a student will face educational difficulties in reading and mathematics.

Brain scans to tailor treatments embody a new form of personalized medicine, an approach that often relies on customiz-

IN BRIEF

There is a dearth of effective treatments for mental illnesses. The drugs and talk therapies available today tend to help some people but not others. Medical professionals need better ways to tailor treatments to individual patients.

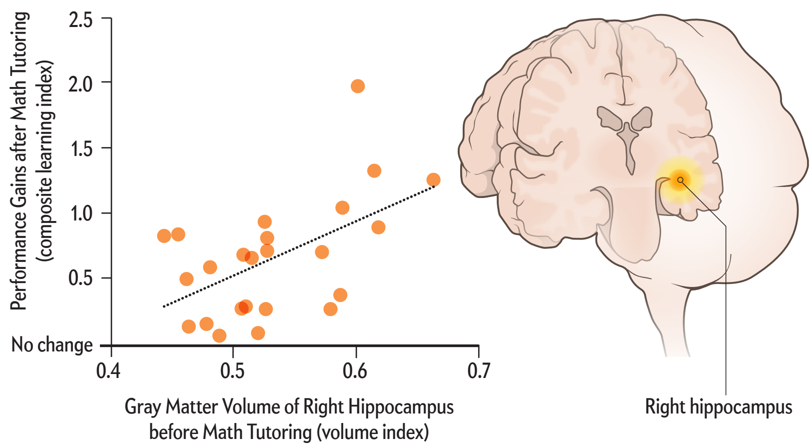
Brain scans show promise in predicting who will benefit from a given therapy. Differences in neural activity may one day tell clinicians which depression treatment will be most effective for an individual or which abstinent alcoholics will relapse.

The same kind of diagnostic techniques could help educators and students. One type of magnetic resonance imaging, for instance, has already predicted better than standard testing which dyslexic children would make progress in reading.

ing therapies based on an individual's genetics. Undoubtedly, genes can predispose a person to mental illness. For any one individual, though, only a weak relation exists between a given gene and common psychiatric disorders. Experience also plays a pivotal role in determining which genes become activated in the brain. Although imaging has many limitations, it approximates what is happening in the brain through the combination of genes and experience. At the moment, it can forecast the prospects for a treatment with greater precision than genetics alone. As these techniques are refined, however, the melding of brain and genetic measures may one day offer still more accurate predictions.

Most Likely to Succeed

In an ideal world, educators would know which students will best respond to which curricula. Researchers at Stanford University set out to see whether brain scans could help achieve this dream. They took 24 third graders and put them in a magnetic resonance imaging machine before they went through an eight-week one-on-one math tutoring program. Students whose scans showed a greater volume of tissue (gray matter) in the right hippocampus had higher performance gains from the tutoring than those with lesser volume in this brain area, which plays a critical role in forming new memories.



SOURCE: "NEURAL PREDICTORS OF INDIVIDUAL DIFFERENCES IN RESPONSE TO MATH TUTORING IN PRIMARY-GRADE SCHOOL CHILDREN," BY KAUSTUBH SUPEKAR ET AL., IN *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES USA*, VOL. 110, NO. 20; MAY 14, 2013

WILL IT WORK?

A STUDY THAT MY GROUP at the Massachusetts Institute of Technology performed in collaboration with clinician-scientists at Boston University and Massachusetts General Hospital demonstrates the prospects for predicting whether a treatment might work. Together we studied how patients with social anxiety disorder responded to CBT. Social anxiety, characterized by an intense fear of interacting with others, remains one of the most common psychiatric conditions in the U.S. Its severe form is often so disabling that the affected person cannot hold a job. In our study, all patients received behavioral therapy. We wanted to find out whether brain measurements taken *before treatment* could predict who would benefit substantially from CBT.

Patients viewed faces with either neutral or negative (angry) emotional expressions while we recorded responses using functional magnetic resonance imaging (fMRI), a type of scan that measures changes in brain blood flow. We also asked a series of questions to quantify the severity of their anxieties. Patients with greater responses to angry faces in regions at the back of the brain, which processes faces and other visual objects, were more likely to benefit from CBT. Using such a brain measure more than tripled the accuracy of predicting which individuals would benefit from CBT compared with results from a conventional severity rating derived from questionnaires.

Another approach we used to assess the effectiveness of CBT combined two techniques. One, known as diffusion tensor imaging, evaluates how well connections established by fiber tracts, or white matter, enable different brain regions to communicate with one another. White matter consists of bundles of long, protruding extensions from neurons called axons that are covered in a whitish, fatty material known as myelin.

The second technique gauges what brain connections link together when a person lies at rest inside the MRI machine. With these data, researchers concocted a map of brain networks. From it, the team created a diagnostic measure, a biomarker, that produced a fivefold improvement in predicting which patients would benefit from CBT. Other studies, such as those by Greg Siegle of the University of Pittsburgh, have confirmed that a similar strategy seems effective in determining how patients with depression respond to CBT.

Predicting the response to a drug for a psychiatric disorder can combine imaging with more conventional types of psychological tests. Andrea N. Goldstein-Piekarski of Stanford University and her colleagues examined responses to antidepressant medications. They interviewed patients about early life stress and then used fMRI to assess activity in the amygdala, a brain structure that processes emotions. In the scanner, patients looked at images of a series of happy facial expressions. Combining information about a person's early life stress and his or her amygdala's responses to faces hinted at whether that individual would benefit from antidepressant medications. The Siegle and Goldstein-Piekarski studies did not compare talk therapy with medication. But Helen Mayberg of Emory University has shown that brain imaging can also reveal whether an individual with depression is more likely to be helped by talk therapy versus a medication.

PREDICTING RELAPSE

TREATMENTS FOR ALCOHOLISM, drug addiction, smoking and obesity share the aim of having users abstain or pare back their use of drugs, tobacco or food. Here, too, imaging techniques may play a role in predicting who will relapse into addictive habits. Half of patients treated for alcohol abuse go back to drinking within a year of treatment, and similar reversion rates occur for stimulants such as cocaine.

Illustration by Falconieri Visuals (brain), Graphic by Jen Christiansen

There is little scientific evidence for determining the length and duration of programs such as a 28-day in-patient rehabilitation at a treatment facility. Research has yet to show whether a shorter or longer course of therapy would prove more effective. Ideally, studies could ascertain if a given patient will relapse in six months or a year, allowing program length to be tailored to an individual's needs.

Imaging studies that make predictions of the outcome for alcohol and drug dependency and obesity are not as common as those looking at depression. Still, a number suggest that brain measures might foresee who will succeed in abstaining after treatment has ended. A study at the University of California, San Diego, found that brain imaging performed at the end of treatment for methamphetamine abuse predicted which patients would relapse during the following 12 months.

Brain assessments can sometimes outperform conventional educational and psychological measures at foreseeing how well a student will do in the classroom.

In an obesity-prevention study using MRI imaging at the University of Alabama, investigators discovered that reward areas of the brain that direct attention to food—the nucleus accumbens, the anterior cingulate and the insula—became active in a group of 25 obese and overweight individuals who looked at images of high-calorie fare before entering a 12-week weight-loss counseling program. Greater activation in these areas predicted who would have the most difficulty in shedding pounds once the program was over. Participants who went into the scanner afterward and who showed high activation of the insula and other attention and reward processing areas had more difficulty in sticking with the regimen nine months later.

Brain imaging may even help formulate the types of messages that health professionals use to encourage patients to adopt healthy behaviors. Emily Falk, then at the University of California, Los Angeles, and her colleagues asked those in their study to learn the proper technique for using sunscreen to prevent sunburn and skin cancers. Researchers recorded fMRI responses as participants watched slides that prescribed preventive measures. Participants then described their attitudes toward sunscreen use and their intentions to use it after receiving a supply of sun-protective towelettes. A week later the group received e-mails asking whether they had actually applied the lotion. Individuals who had logged greater activity during the viewing session in one brain area, the medial prefrontal cortex, which regulates beliefs and a sense of self, ended up using more sunscreen. Brain scans provided an objective measure of the program's effectiveness, extending beyond an individual's subjective evaluation of whether the health information helped.

Observation of brain activity may also assist in discovering the best approach to dissuade people from continuing to smoke. A 2010 paper in *Biological Psychiatry* from Harvard Medical School found that among 21 women, a high response to smoking-related pictures in two brain regions—the insula and the dorsal anterior cingulate cortex—forecast an inability to quit.

BETTER LEARNERS

CHILDREN'S EDUCATION might benefit as well from brain imaging to predict difficulties in learning to read (dyslexia) or do math (dyscalculia). Teachers and parents try to help, but education operates largely on the model of waiting to fail. Students receive some guidance from teachers until they reach a point when they become discouraged, and then learning tends to break down.

What if instructional support did not merely react to failures but could anticipate specific forms of teaching that could be adapted to the needs of individual students? Some recent findings indicate that brain imaging can help predict students' future performance. Brain assessments, in fact, can sometimes outperform conventional educational and psychological measures at foreseeing how well a student will do in the classroom.

Among children with dyslexia, individuals vary greatly in their ability to compensate for reading difficulties by devising their own strategies that let them catch up to their classmates. Fumiko Hoeft, now at the University of California, San Francisco, and I measured brain fMRI responses to printed words in children with dyslexia around 14 years of age who also received extensive psychological testing. Then we examined the same children again 30 months later to see how much they might have improved in reading. About half the children exhibited substantial gains.

None of the standard educational testing measures correlated with future reading progress, but the brain scans combined with an analytical technique could make such predictions. Pattern-classification analysis, which delves into the complex data from fMRI brain scans using "big data" machine-learning algorithms, yielded more than 90 percent accuracy in characterizing whether a dyslexic child's reading would improve or continue to flounder two years after the images were captured. Other researchers have reported that electrical responses on the scalp (evoked response potentials) in young, preliterate children also predicted reading skills. Knowing what lies ahead may allow interventions prior to encountering reading difficulties, a strategy that spares children the sense of failure evoked by early struggles.

Math teaching may also profit. A study conducted by Vinod Menon of Stanford found that brain anatomy could identify whether a third grade student had more of a chance of benefiting from a math-tutoring program that encouraged students to shift from counting to arithmetic fact retrieval (memorizing 2 + 3 = 5, for instance) as a basis for arithmetic problem solving. Conventional behavioral tests of math abilities or IQ failed

to predict which student would not be helped by the program, but brain measures succeeded. In particular, the size of the right hippocampus, an area associated with memory, correlated with how much a student would progress.

These studies hold promise of laying the basis for a neuroscience-based methodology of personalized learning. If this research can eventually identify the best instructional approach for a student, educators could avoid the failures that occur later in childhood or adolescence when learning difficulties become more difficult to correct.

WANTED: BETTER PREDICTIONS

IF BRAIN MEASURES SHOW such promise for predicting whether an individual will respond to a mental health treatment or schooling, why are these methods not already in use? Several challenges linger before these techniques enter clinics and schools. First, the predictions need additional statistical rigor. In the studies so far, models have linked brain activity to already known outcomes, such as how much an individual benefited from a treatment. In that sense, they might be called postdiction rather than prediction. New studies must now ascertain whether these findings routinely make accurate forecasts.

For the prediction sciences to move forward in mental health and education, the research community must begin to design studies that compare results for two independent groups. A mathematical model from one group can be tested on the other to validate the model.

One intriguing approach known as leave-one-out cross-validation excludes an individual from the overall evaluation of the results of the group under analysis. Researchers create a model from other individuals in the study to predict a particular health or educational outcome. The model then goes on to forecast a result for the left-out individual. The entire process repeats for each study participant with the goal of creating a model that better guides selection of each new patient's treatment. Only a handful of studies have achieved such a high standard to date, but this level of rigor must be met for the practical use of brain imaging as a prediction technique.

Another barrier relates to the cost and availability of MRI brain imaging. Any economic calculation must balance the price for the procedure, which is often about $500 to $1,000 per hour, against the prospect of having to pay for physician and hospital visits, lost work productivity and special education resources to support students falling behind. In some cases, other technologies might substitute for MRI, even while borrowing knowledge gleaned from the more expensive technique. Electroencephalography, which measures the brain's electrical activity, might, for instance, be adapted to take the place of MRI in some types of testing.

The promise and potential controversy surrounding MRI for clinical use show up in two recent studies. One by Joseph Piven of the University of North Carolina at Chapel Hill used fMRI to image 59 infants who were six months old to detect a heightened risk for autism spectrum disorder (ASD). The defining social and communication difficulties of autism rarely emerge at birth but typically only, with careful evaluation, at two years of age. Imaging studies of brain network activity at six months predicted correctly nine of the 11 infants who would be diagnosed with ASD some 18 months later. And the measurements also established that the other 48 would not be so classified. This kind of prediction could one day both calm the worries of parents whose infants will not progress to ASD and assist in devising early interventions to aid children at high risk.

Another prediction study attempted to build on evidence that impulsivity appears as a major risk factor for recidivism. A measure of brain activity for self-control could potentially help address the limited accuracy of expert advice in making decisions about bail, sentencing and parole. Kent Kiehl, a professor of psychology, neuroscience and law at the University of New Mexico, examined brain activity during an impulse-control task in 96 male offenders before their release from prison and then followed these men over a period of several years. The offenders performed a task during brain imaging intended to make impulse control difficult. They had to press a button as the character "X" appeared repeatedly on a computer screen. At the same time, they had to resist the temptation to press the button in the rare instances that the letter "K" appeared, thereby creating two conflicting impulses, depending on what was displayed on the screen.

The lab task helped to predict what happened to the men after their release from prison. The likelihood that a former inmate would face another arrest over a four-year period doubled if the offender had diminished activity in the anterior cingulate cortex, a brain region involved with cognitive control and resolving conflicting impulses. Brain scanning helped to better forecast future rearrest than conventional measures alone, such as scores on a psychopathy checklist, age or lifetime substance abuse. An unpublished reanalysis of the data by Russ Poldrack, now at Stanford, suggests that the strength of this prediction lessens considerably when applying these results to prison populations other than the one surveyed (a suggestion partially countered by Kiehl and his colleagues).

All these studies raise a set of critical issues. How accurate should a prediction be to improve mental health treatments and educational practices? As a corollary, how can predictions made from brain scans help people rather than curtail their educational or employment opportunities? If we could better project future mental health or learning difficulties or even criminal activities, how would we, as a society, ensure that such predictions do not justify punitive policies and instead promote individual well-being? Ironically, the better prediction becomes over time, the more pressing the need emerges for an ethical framework to use such knowledge wisely. SA

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MEDICINE

THE MEANS OF EPRODUCTION

Could scientists one day use blood and skin cells to replace sperm and eggs?

By Karen Weintraub

Illustration by Raul Arias

Karen Weintraub is a freelance health and science journalist who writes regularly for the *New York Times,* STAT and *USA Today,* among others.

THE MICE SCURRYING AROUND THEIR CAGE IN KATSUHIKO HAYASHI'S LABORATORY DO NOT LOOK remarkable. They run, eat and sleep like others of their kind. But these eight rodents have an unusual origin story, one that Hayashi, a reproductive biologist at Kyushu University in Japan, revealed two years ago in the pages of *Nature.* The tawny-colored mice, he and his colleagues announced, did not spring from the mating of sperm and egg. On their mother's side, their roots trace to a reprogrammed skin cell.

The advance, called "amazing" by other researchers, delivers on a promise hinted at in 1997, when scientists managed to clone Dolly the sheep. That accomplishment built on earlier cloning work in frogs from the 1970s and taught scientists that every animal cell has the same basic set of instructions. By transforming a sheep's mammary cell into a living animal, Dolly's creators showed that every mammalian cell has the same genes—and that the difference between a breast cell and any other cell is simply which genes are turned on or off.

For Hayashi and other scientists, that work created the prospect that they might be able to reprogram mammalian cells to become anything from a neuron to an egg if only they could devise the right instruction manual. A small number of researchers around the world, including Hayashi, are using this legacy to tackle in vitro gametogenesis—generating eggs and sperm from adult cells.

Reproductive scientists and some couples struggling with infertility are closely tracking Hayashi's progress, as well as similar efforts that have successfully converted rodent stem cells (progenitor cells that can develop into any type of specialized cell) into rudimentary sperm. If these egg and sperm techniques can be made to work in humans, we may one day be able to replace our faulty gametes with blood or skin cells. In that future, men would not have to worry about a lack of healthy sperm. And instead of watching their chances of motherhood fade with their 30s, women of virtually any age could give a little blood and end up with a batch of eggs. Gay couples, too, might one day be able to have children to whom they are both biologically related.

The hope remains tantalizing but distant. Years of animal experiments aimed at finding a reliable substitute for the egg and sperm cells essential to creating most mammalian life have come up short. Yet even this very preliminary work in mice is prompting a wave of ethical questions from the scientific community about eventual human applications.

PLANNING PARENTHOOD

TO MAKE THIS REPRODUCTIVE PROCESS WORK in mice, Hayashi's team needed to tie together several earlier discoveries. In 2010 it practiced hitting the "reset" button on cells, sending them back to a stage before they had found their identity. The team began by retracing a process developed by Shinya Yamanaka of Kyoto University in Japan, who won a Nobel Prize for the work in 2012.

First, the researchers scraped skin cells off an adult mouse's tail. They then injected them with a chemical cocktail containing four specific genes to transform adult cells back into stem cells capable of becoming many different kinds of cells. Next, they employed genetic insights established in the early 2000s by Azim Surani of what is now the Gurdon Institute in England and Mitinori Saitou, who was then working in Surani's lab. (Both men would later mentor Hayashi.) This work, and related experiments with embryonic cells derived from regular mouse embryos, eventually helped Hayashi's team understand which genes would be needed to coax stem cells into becoming egg progenitor cells called primordial germ cells.

There was a catch: primordial germ cells, which can develop into either sperm or eggs, still have two sets of chromosomes like any typical animal cell. To form sex cells, which have just one set of genes from each parent, germ cells must twice undergo cell division in a process called meiosis. In females, the first cell division happens in the embryo as the primordial germ cell enters the reproductive system. The second division happens during ovulation when the egg is finally matured after exposure to a number of hormones. After creating the primordial germ cell, Hayashi and his co-workers were able to place them back into a

IN BRIEF

Mammals typically require eggs and sperm for reproduction.

Recently scientists have managed to convert skin stem cells into viable eggs in mice.

In 2016 researchers created eight healthy mice by coupling eggs derived from skin stem cells with standard mouse sperm.

Scientists hope these accomplishments will eventually lead to more future reproductive options for human infertility.

live mouse to complete their development—reaching what was then the boundary of science. To create viable eggs in a dish, however, researchers would need to understand and re-create each step along the pathway to maturation.

The key, the scientists discovered, was to more carefully mimic nature. They spent several years tweaking the solution in which the converted egg cells were grown. One breakthrough came when the team added cells from ovaries of other mouse fetuses into the medium while they matured the cells in a dish. The ovaries released a mixture of hormones—basically creating an ovarylike environment to fool the cells into thinking they were in the body. Furthermore, the scientists altered the viscosity of the fluid medium to mimic what would be found in the mouse.

Once they got that medium right, and the eggs were matured in the lab, the next steps were akin to any other in vitro fertilization (IVF) procedure. The researchers first married the mature eggs and normal mouse sperm together in the lab. After a few days, they selected a promising embryo using a tiny pipette and injected it into a female mouse that would incubate the mouse fetus for 20 days. Finally, after many failed attempts in which the mouse would miscarry, or the embryo would not implant, or it would become stillborn, the process at last led to one healthy pup. Eventually more followed.

The process is still far from perfect, however. Only 16 of the hundreds of stem cells Hayashi's group created survived the five-week mouse-egg-maturation process. And when the scientists coupled the successful lab-made eggs with sperm, only an extremely small percentage of those skin-cells-turned-eggs went on to become healthy mouse pups (compared with a 62 percent success rate for eggs taken from adult mice and fertilized in vitro). Yet the scientists proved that their methods could work. Those eight pups grew up to be normal and healthy. They even went on to have mates and birth lively pups of their own.

WHEN SPERM MEETS EGG

PLENTY OF PEOPLE require reproductive help. More than 10 percent of American men and a similar percentage of women are considered infertile. Options for overcoming infertility are arduous and often unsuccessful. IVF, for example, requires a woman to undergo a week or two of hormone shots designed to release multiple eggs. A handful of those eggs will then be fertilized with sperm in a lab, and one or two will be implanted. The cost, largely paid out of pocket, can easily top $20,000, and yet approximately 65 percent of in vitro fertilization cycles still fail, often because of poor egg quality. Moreover, IVF cannot help if someone has no healthy eggs or sperm.

It is obvious why mining human blood or skin cells to make a baby is an alluring alternative. Instead of extracting human eggs, a health care worker could draw a small vial of a potential mother's blood. (Blood, which is routinely drawn in medical facilities, might be easier to access in human patients than skin cells, Hayashi says, although either could be used.)

Scientists in a lab could transform those blood cells into stem cells and then, after a few more steps, into eggs or sperm. Next, the manufactured egg could be fertilized with normal sperm, or vice versa, and implanted into the woman using the same method as IVF—leaving the child with the same genetic inheritance he or she would normally get from each parent.

A Recipe for Making Babies from Skin Cells

In pursuit of a workaround for female infertility, Katsuhiko Hayashi of Kyushu University in Japan and his colleagues have been trying to find a way to convert skin cells into viable eggs. After thousands of failed experiments, in the fall of 2016 they managed to find the right chemical milieu and laboratory conditions to reprogram skin cells from mice into viable gametes. Next, they were able to use in vitro fertilization technology to marry those lab-grown eggs with standard sperm. Eight healthy mice have been born as a result of this breakthrough. The insights from this technique, researchers hope, could edge science closer to new options for humans.

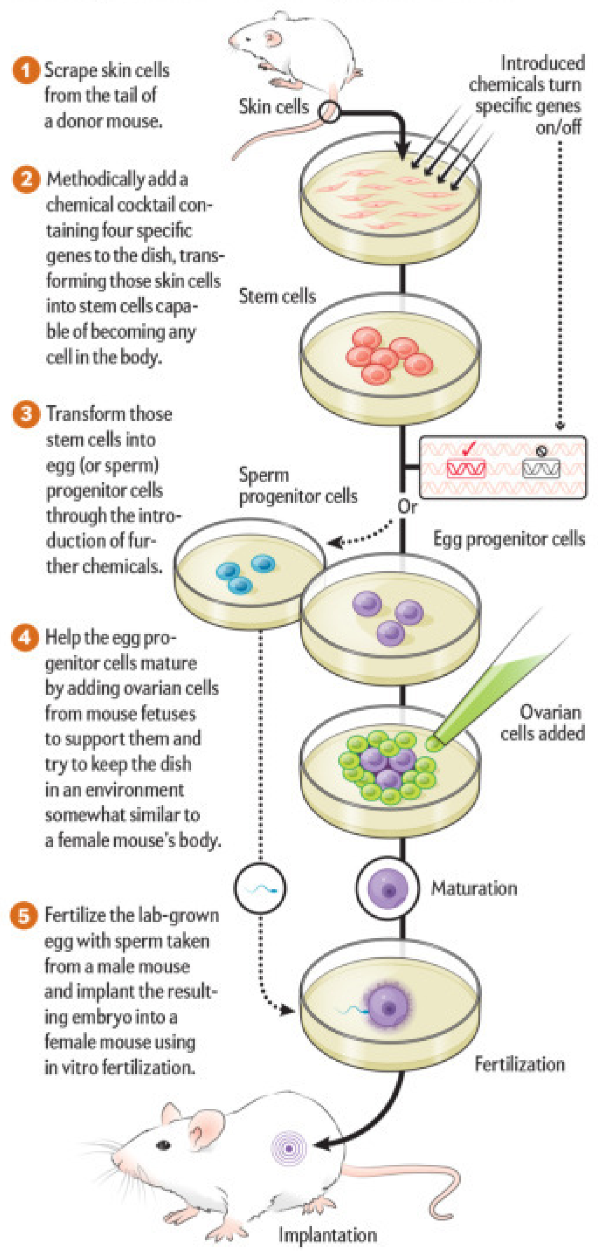


Illustration by Tami Tolpa

Hayashi says that right now the procedure is too risky to apply to humans and would become acceptable only if the eggs that scientists create can lead to healthy embryos as often as natural ones do. To begin with, researchers will have to show that they can keep the eggs alive in the lab long enough to closely emulate what would be necessary for human development. (In the mouse, egg cells mature in five days, but in women, they require roughly 30.) Yet before reproductive scientists can even think about doing this work on human cells, they will have to confirm that the process will work in larger animals that more closely resemble people.

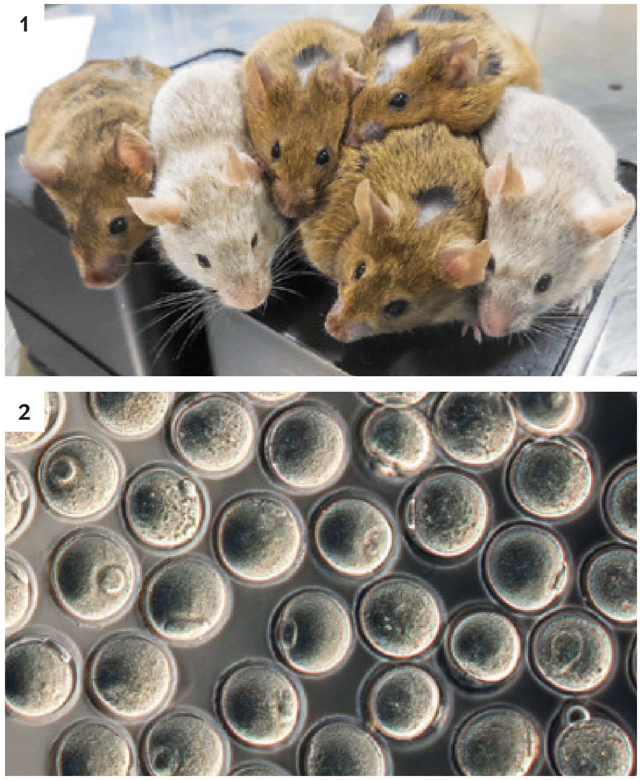
GROWING TOGETHER

TO OVERCOME THAT HUMP, Hayashi's team is already working with primates: marmoset monkeys. But several major challenges have hindered its progress. Mice are good research subjects because they ovulate every five days and are pregnant for 20. Marmoset pregnancies last more than 140 days, so creating a baby would take longer, even if all the science worked perfectly. It takes much longer for primordial germ cells in a marmoset to mature into eggs than it does for mouse eggs to mature, and Hayashi and his team have yet to find a lab environment that keeps the cells alive long enough for that to happen.

In their rodent work, the researchers learned how to mature primordial germ cells outside of living mice, but they still needed ovarian cells from mice fetuses to aid the process. To make sure the primordial germ cells survive and mature in monkeys—and to be able to scale up this work to ultimately create many more lab-grown eggs—Hayashi thinks he will have to do more than simply transfer ovarian cells to a lab dish. He will have to identify the specific ovarian cells that send key signals for maturation and figure out how to make them from stem cells. That way, in future stages of the work, he would be able to grow all the necessary ingredients—rather than remain dependent on mining other fetuses for their ovarian cells.

Surani, director of germ-line and epigenomics research at Gurdon and a pioneer in this field, has been experimenting with different combinations of these key "helper" cells to support the germ cells' maturation and communication. "The [germ] cells actually go through to a certain point, and then they need something very specific to break through the next point—they need a change of signal or environment—or something," Surani explains. He and his team have been making educated guesses about which cells may be particularly significant in that process, but it is slow, painstaking work. To help guide their next steps, they are now studying aborted human fetuses for clues about each step of egg cell maturation. The lab has also started using pigs, instead of mice, because porcine development more closely resembles that of humans and because pigs are cheaper to work with than monkeys.

Rather than tweaking lab dish protocols, there might be another way to further the process. Some researchers think they will get better results by moving their manufactured cells in vivo as soon as possible to piggyback off the body's natural quality-control systems that eliminate flawed gametes and leave more resources for the remaining cellular contenders. Renee Reijo Pera, a stem cell scientist at Montana State University, is taking that tack in her work with sperm. In nature, only the fittest sperm survive to fertilize the egg, but making and maturing



MICE CREATED from lab-made eggs and typical mouse sperm are healthy (*1*). These eggs were derived from embryonic stem cells (*2*).

KATSUHIKO HAYASHI *Kyushu University*; FROM "MOUSE EGGS MADE FROM SKIN CELLS IN A DISH," BY DAVID CYRANOSKI, IN *NATURE*, VOL. 538; OCTOBER 20, 2016

sperm in a lab dish does away with that competition, increasing the risk that defective sperm will fertilize, she says. Because the human body is exquisitely tuned to weed out bad sperm, Pera focuses her work on making primordial sperm that can be matured in the testes. "We think the body should do the selecting," she says. "In a dish, I'm worried we'll force things to go forward that wouldn't in the natural environment."

No matter what precautions scientists take, some critics say artificial eggs or sperm should never be used to create human life. Marcy Darnovsky, for example, does not think that lab-generated germ cells could ever be safe enough to justify their risks. Darnovsky is executive director of the Center for Genetics and Society, a public-interest organization working for the responsible use of human genetic technologies. She says she fully supports research that leads to a better understanding of human and animal development. But she draws a line at using engineered eggs and sperm to generate a new life—especially a human one. "I think it's likely to be extremely biologically risky for any resulting children," she says, citing the example of mammalian cloning: many of the cloned embryos failed to develop, and some animals were born with terrible health problems. Darnovsky believes that public policy is needed to make sure that the scientific progress Hayashi, Surani, Reijo Pera and others are pursuing does not go too far.

Other concerns persist about what this methodology might mean for our understanding of parenting. If anyone's cells could be manipulated into becoming sperm or egg, for example, could

that portend a future where individuals' cells could become both sperm and egg—creating a uniparent? Or might someone be able to snatch up a stray skin cell from a person's napkin or bed to create a child without his or her consent or knowledge? Moreover, as George Daley, dean of Harvard Medical School, and his colleagues wrote last year in *Science Translational Medicine,* such a technology could enable the creation of embryos on a previously unimagined scale—raising the specter of the devaluation of human life, as well as vexing policy challenges.

Ethical concerns have thus far constrained any human-related work on in vitro gametogenesis and have kept funding to a minimum, researchers say. Science involving embryos has long been restricted in the U.S. Whereas the Obama administration was friendlier to stem cell research than its predecessor, many expect that the pendulum will swing back under Donald Trump. In other countries as well, the lack of funding for such research and difficulty in accessing tissue samples of natural embryos for comparison add an extra layer of challenge to the research, according to Surani and Helen Picton, who does related work at the University of Leeds in England. Hayashi, for example, says it would be very difficult for him to do human germ cell studies in his native Japan. (Japanese law forbids fertilizing human germ cells, even for research work.) But Jacob Hanna, a stem cell scientist at the Weizmann Institute of Science in Israel, says he has an easier time because of cultural interest in advancing reproductive technologies.

AN ETHICAL CONUNDRUM

EVEN IF THEY NEVER produce a human baby, though, scientists say simply pursuing the goal of making eggs and sperm will have payoffs: in treating infertility, understanding early development and unraveling the effect that toxins can have on human inheritance. "It's a voyage of discovery," says Picton, who specializes in ovarian physiology and reproduction. Figuring out how to identify high-quality eggs and sperm may help improve the selection process for IVF, for example. And the process of refining the recipe for gamete creation will provide the first real insights into where cells go wrong to cause disease, birth defects or cellular death.

Learning how to make eggs and sperm from skin or blood cells might also help scientists better unravel genetic inheritance known as epigenetics—changes not to the genes but to gene expression. Understanding how sperm and eggs are formed in their earliest days might allow us to scour those cells for any methyl groups or other changes that have accumulated in the genes. Right now questions abound regarding how some traits seem to get passed down without altering the underlying genetics. In a 2016 study, for instance, epigenetic changes to areas of genes associated with regulating stress hormones were found in the children of Holocaust survivors born years after their parent's trauma. The genes were unchanged, but how the genes acted seemed to get passed down. Being able to generate eggs and sperm from stem cells could allow scientists to dig into this epigenetic process, Surani says, and could offer insights into diseases of aging, which are often caused by the accumulation of epigenetic markers. Treatments for aging-related diseases might even come out of a new understanding of how these marks are erased in the developing germ cell.

Surani is currently researching how mitochondria—the cells' energy source—perform during the egg-making process. Mitochondria go through a selection process during reproduction, with the child receiving only his or her mother's genetic material. The process of correcting defects in mitochondria is not well understood, but Surani hopes that by studying how the germ cell corrects such errors, he and his colleagues can learn a lot about cellular energy and related diseases. "Along the way, we can gather knowledge that could have a huge impact on human health," he says.

Hayashi hopes that the work will also be useful for rescuing and restoring nearly extinct species, such as the white rhinoceros. By improving their understanding of the process of forming gametes, researchers will be better poised to work with species that are likely to die out, he says. He is now trying to reproduce his mouse research with white rhino cells, but progress has come slowly. In addition to all the differences in the species' reproductive processes, the wait time is much longer. A mouse is pregnant for 20 days; a white rhino is pregnant for 16 months, he notes.

When Hayashi talks to audiences about his white rhino work, everyone looks happy, he says. But when he mentions doing similar research in humans, "some people are very skeptical, and some are very afraid." Hayashi understands their concerns. A lot of human germ cells and embryos would be wasted before human stem cells could successfully be transformed into viable eggs and sperm. Even the viable gametes might still carry the risk of birth defects, he cautions.

Reijo Pera believes that ethics do support studying this work for human applications—and, if it can be done safely enough, even using it to create humans. A cancer survivor who is infertile herself, Reijo Pera believes that helping couples have children justifies the quest.

Yet thorny questions remain about exactly what should be considered safe and who should decide that. When scientists developed other contentious technologies, such as IVF and the gene-editing CRISPR system, formal meetings among researchers, ethicists and members of the public helped to develop recommendations and guidelines for their potential applications. The same will likely be required for in vitro gametogenesis, researchers and ethicists note. Moreover, those conversations should take place long before the science is at a stage where humans can use it. "Before the inevitable, society will be well advised to strike and maintain a vigorous public conversation on the ethical challenges of [in vitro gametogenesis]," Daley and his colleagues wrote in their January 2017 paper. "With science and medicine hurtling forward at breakneck speed, the rapid transformation of reproductive and regenerative medicine may surprise us." SA

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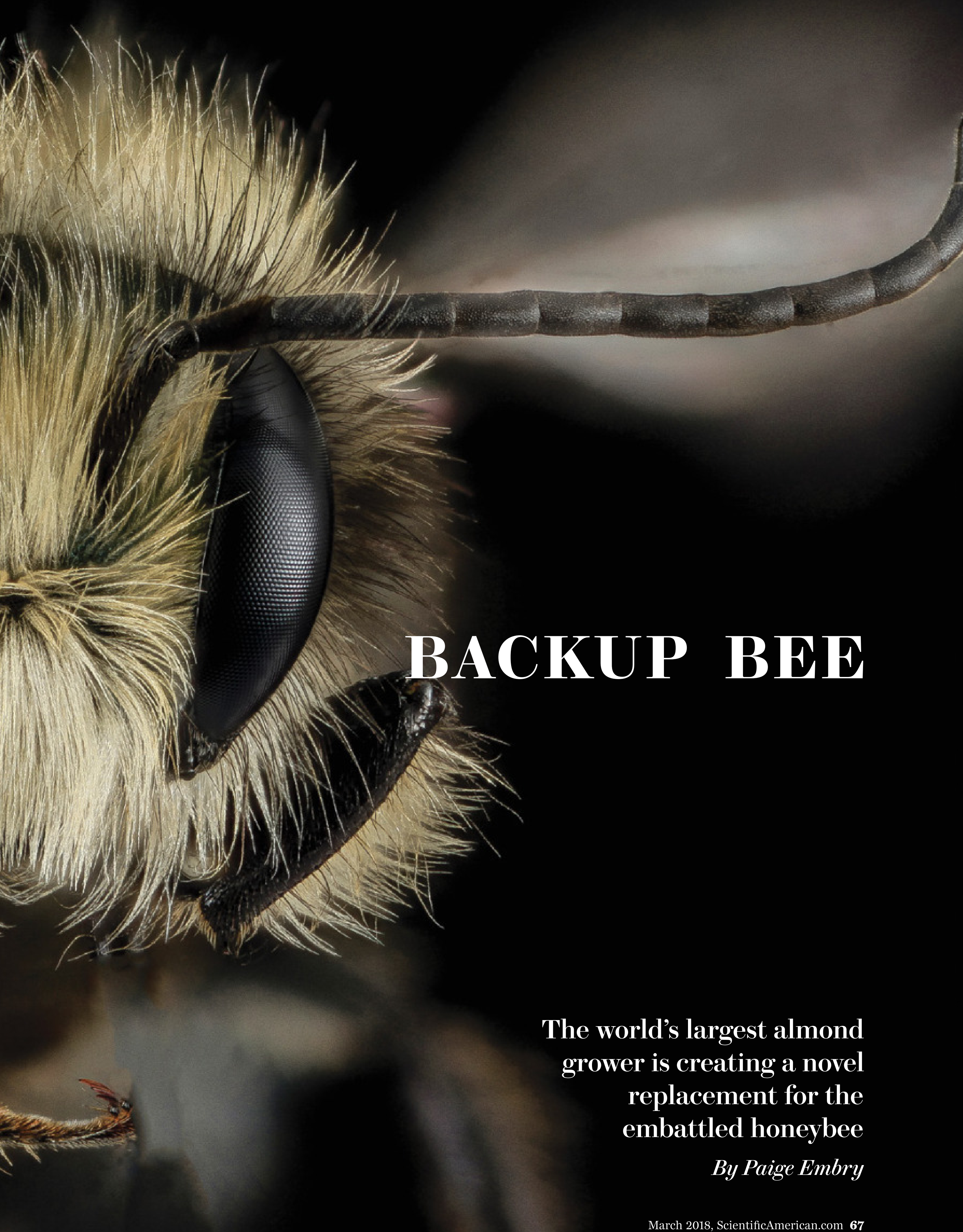
AGRICULTURE

BUILDING A

ONE BLUE ORCHARD BEE can do the work of many honeybees.



BACKUP BEE

The world's largest almond grower is creating a novel replacement for the embattled honeybee

By Paige Embry

EVERY FEBRUARY AN EXTRAORDINARY RESEARCH project resumes in the southwestern corner of California's Central Valley. It takes place inside a series of huge cages that span 20 acres by a vast pistachio grove. Each cage is shaped like a rectangular warehouse but is made entirely of extremely fine netting, pulled tight and straight along strong, narrow beams to form see-through walls and ceilings. The experiment is run by Gordon Wardell, director of bee biology for the Wonderful Company, the largest almond grower in the world. For the past eight years Wardell has been using these cages to develop an alternative insect to replace the honeybee.

Paige Embry is author of *Our Native Bees: North America's Endangered Pollinators and the Fight to Save Them* (Timber Press, 2018). She lives in Seattle.

The need for a backup bee has become critical, particularly in almond orchards. Almonds are California's second-largest crop, injecting an estimated $21 billion annually into the state's economy. In 2016 California's almond growers needed nearly 1.9 million honeybee colonies—almost three quarters of all the commercial colonies in the country—to pollinate their 940,000 acres. Every bag of salted almonds and box of almond milk the industry produces relies on honeybees. But they are in trouble, beset by an avalanche of problems, from deadly pests and diseases to poor nutrition and pesticide exposure.

Annual colony losses in the U.S. for the past 11 years have ranged between 29 and 45 percent. Add in the ever expanding almond acreage—from 570,000 acres in 2004 to more than a million today—and the entire system is stretched. At the National Stakeholders Conference on Honey Bee Health in 2012, Jeff Pettis, then with the U.S. Department of Agriculture, said, "We are one poor weather event or high-winter bee loss away from a pollination disaster."

Wonderful hired Wardell in 2009 to avoid such a disaster in its orchards. The company chose to develop *Osmia lignaria,* a native mason bee known as the blue orchard bee, or BOB. It was an excellent almond pollinator; it had done well in small studies and had relatives that European and Japanese growers were managing successfully. And there was no alternative. Only about a dozen of the 20,000 or so bee species worldwide are managed. After the honeybee, *Apis mellifera,* only three species are widely used in the U.S.: two cannot be woken from their winter's sleep in time for almond bloom, and the third is banned for open field use in California.

BOBs are nothing like honeybees, however. Honeybees are social. One queen and thousands of female workers live together in colonies that can last for years. Multiple generations of workers divvy up the jobs that keep the hive functioning. BOBs are solitary, spending their entire lives alone except when they mate. Mating is a male bee's only job. Because they do not collect pollen for the babies, males often are not even counted in pollination work.

Each female is both queen and worker in her little domain. After a female mates, her only job for the rest of her adult life (about another 20 days) is providing for her offspring—usually between seven and 12 in orchards. She collects pollen and nectar, forms it into a wad, places it in an aboveground hole and lays an egg on the mixture. Then she walls it in with mud, never to see her offspring. The young bees eat, grow and sleep in these mud-walled nurseries and do not emerge until the following year. Any loss of a BOB female matters: it permanently reduces the current year's pollination workforce and diminishes next year's

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crew because fewer eggs are laid. The loss of one honeybee, in contrast, is trivial because a healthy colony generates tens of thousands of workers across a year.

With only one generation annually, it is not surprising that it has taken Wardell so long to figure out how to mass-produce BOBs. "If you make a mistake, you have to wait a whole year to make another mistake," he says. "My boss doesn't appreciate the humor in that."

IN BRIEF

Almond grower the Wonderful Company is developing the blue orchard bee, or BOB, as a replacement pollinator for the honeybee, which continues to struggle. BOBs are highly efficient; a few hundred females can do the work of 10,000 honeybees.

BOBs do not naturally multiply well in monoculture orchards common in the U.S. But this spring biologist Gordon Wardell will put 128,000 BOBs, raised in vast cages, into the company's California almond orchards to pollinate trees.

If the effort succeeds and breeding costs stay low, more nut and fruit growers may opt for BOBs, altering pesticide regimens and other practices to help BOBs thrive—finally creating a viable alternative to renting honeybee colonies.

PRECEDING PAGES: LAURA CAMPBELL AND U.S. GEOLOGICAL SURVEY; THIS PAGE: JAY DUNN (1)

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BIOLOGIST GORDON WARDELL handles almonds in California's Central Valley (*1*). He is breeding the blue orchard bee inside large, netted cages there (*2*) to back up the struggling honeybee as the pollinator of choice for the state's vast almond orchards.

Wardell has investigated all aspects of BOB life in those cages and has figured out how to do what no one else has: economically raise large numbers of BOBs on a small parcel, making them a commercially viable alternative to honeybees for almond pollination.

In 2017 Wonderful needed about 76,000 honeybee colonies to pollinate its almonds (at two colonies per acre). But that number will diminish by 320 this spring because Wardell will put 128,000 female BOBs into the orchards—the largest deployment ever. If Wardell's experiment succeeds, the results could have far-reaching implications for the almond industry as well as a host of other early-blooming crops—from apples and cherries to apricots and peaches. All told, more than a million and a half acres could benefit from having BOBs as a backup—if they prove worthy this year. It has taken years to get this far, and problems still await.

BRINGING A BEE TO MARKET

COMMERCIALLY MANAGING a bee requires affirmative answers to four questions: Are the bees effective pollinators of the intended crop? Can they be awakened and transported to the field in time to pollinate? Can they be easily managed in the field? And can a critical mass of bees be produced economically?

In the 1970s Phil Torchio, a scientist at the USDA's bee lab in Logan, Utah, investigated BOBs and found them to be excellent pollinators of early-blooming fruit and nut trees, a finding supported by later studies. On a bee-to-bee basis BOBs are vastly more efficient than honeybees. A few hundred females can do the pollination work of 10,000 honeybees. Torchio found that the bees could be woken up from diapause, a dormant state, and delivered to the crops when needed. He also developed the first protocols for managing BOBs.

Scientists have been working since Torchio's time to find the best ways to manage BOBs in the field. They have studied mud types and the size, material and color of nest blocks, as well as the best locations for the blocks in an orchard. The progress is of little commercial value, however, if growers cannot deploy enough bees to make a difference, at a price they can afford. This is the problem Wardell has cracked.

In an ideal world, BOBs would be raised in the fields they pollinate. In Europe, farmers get a threefold to fourfold increase of European *Osmia* bees out of their orchards every year. Jordi Bosch, who used to work for the USDA and is now at the Center for Ecological Research and Forestry Applications in Spain, says this happens because European orchards tend to be smaller, contain a mix of fruit species and have a variety of weeds that bloom around them at various times. Those factors help bees live out their full adult life span, so they can lay many eggs. In California, large, weed-free, monocrop orchards provide only two to three weeks of one type of bloom—insufficient for maximum egg laying. Fungicides and pesticides can further reduce the number of progeny that an orchard produces.

Historically, people obtained BOBs by trapping them in the wild, but this method is slow, and numbers can vary significantly from year to year. Wardell believed he could raise large numbers of BOBs consistently if he could just control the weather—which he has essentially done by locating his bees in the southern Central Valley. Reliably sunny days and appropriate temperatures during the BOBs' flying season allow him to raise up to

JAY DUNN (2)

two million bees on a mere 20 acres of land inside his cages.

Still, Wardell has had to optimize all the past research to raise his bees. He has tested and monitored every aspect of the bees' lives, from the plant species needed for food to the kind of mud the bees use to build the walls between their nest cells.

15 MILLION BEES A YEAR

WARDELL'S ULTIMATE GOAL is to raise enough BOBs to cover half the 76,000 honeybee colonies used to pollinate Wonderful's 38,000 acres of almonds. That will take 400 BOB females per acre—15.2 million female bees a year—plus all the males. Wardell has a two-pronged plan to meet that goal.

The first step is to raise a million female BOBs a year in his cages. That has to be done during a few frantic months in spring. Wardell and his crew erect the cages, put in plants, install mud pits and nest boxes, then add the bees. About 300,000 to 350,000 females from the previous year go into the cages to lay eggs. The rest go into the orchards. After the almond petals fall and the cage flowers die, the BOBs in the field and the cages metamorphose. In autumn Wardell's workers bring the blocks inside and remove and store the cocoons. They chill the cocoons for winter and warm them when next year's bloom time arrives. The storage phase can be perilous. Wardell says he sometimes lies awake worrying that a pest or disease will race through his cocoons. He x-rays them regularly, looking for trouble.

The second step requires getting a 100 percent return from the bees put in the orchards. As noted, monocrops are not ideal for bee reproduction, but modifying pesticide regimens and planting alternative forage, as European growers do, can help. Wardell also hopes to improve returns by honing the bees' wake-up time so that their adult life cycle lines up as closely as possible with the almond bloom. That way he may avoid "the bees hanging around hoping for handouts after the bloom."

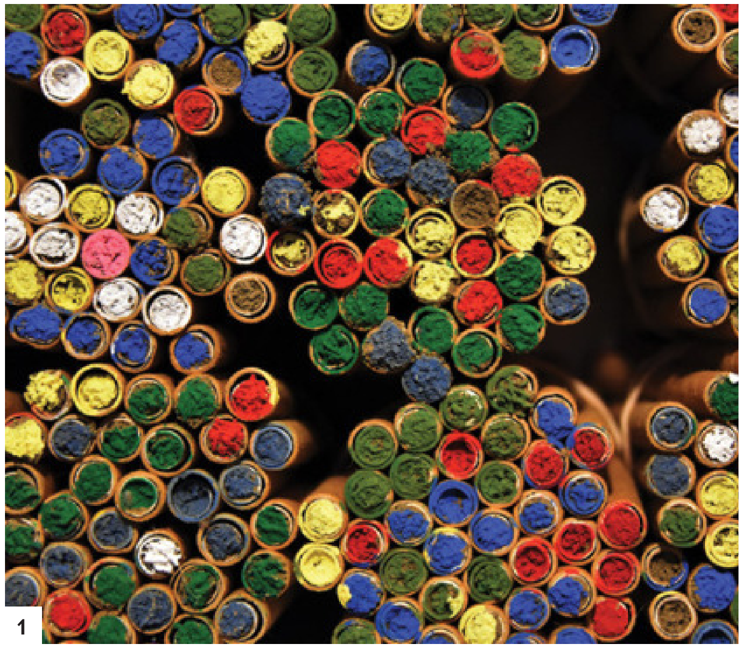
Last year Wardell met his 100 percent in-orchard target: 100,000 female BOBs went in and laid enough eggs so that 100,000 came out. But he was well shy of his goal of a million females from the cages because of problems with nest materials and workforce issues that led to planting delays, giving the bees a short flying season.

In 2017 the orchard BOBs supplemented the normal complement of honeybees. This year will be the first time Wonderful substitutes BOBs for some of its honeybees—those 320 colonies. If Wardell consistently meets subsequent annual goals, it would still take more than 20 years to replace half the company's honeybees, although the process could be sped up by adding more cages. This is a long-term strategy for Wonderful, one it hopes will help spread its risk and control its pollination destiny.

It costs Wonderful 22 cents to produce one female BOB. That means one honeybee colony can be offset with 400 females for $88, plus start-up costs. The average colony rental rate for almond growers in 2016 was $167. So Wardell has indeed shown that large numbers of bees can be raised consistently and affordably.

THE TIPPING POINT

DESPITE WARDELL'S SUCCESS, BOB sellers and orchard growers are not rushing to build their own cages. For one thing, a project such as Wardell's requires extensive resources. Jim Cane is a research entomologist at the USDA's Utah bee lab and has worked with agricultural pollinators for decades. In an e-mail to me, he wrote



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of Wardell's work: "His success in mass-propagating BOBs is a landmark that can only be achieved in a commercial setting (a research lab like ours simply lacks the acreage, personnel, money, equipment and farming experience to make this work)."

Moreover, sometimes the model fails. Investors started AgPollen in 2007 to develop BOBs as a commercial pollinator but never got consistent bee returns from the cages. Steve Peterson, the scientist who ran the project, blamed its failure in part on pesticide use on surrounding properties.

Another concern is that Wardell's bees come from one site. If something goes wrong, all is lost—at least for that year. It happened once. Wardell's plants died, and with little native forage available, most of his bees soon followed. "Growing these things is like trying to overcome the seven plagues of Egypt," Wardell says. He has had invasions of fungi, birds, mice and even toads, which sat by the mud pits "eating blue orchard bees like candy."

Other breeders have their own demons. Jim Watts runs Watts Solitary Bees. He lives in western Washington's wet, variable climate and fears bad weather. He traps BOBs in the wild from different locales, hoping that by doing so he will avoid a weather-related catastrophe. His approach does not have hefty start-up costs, can be done wherever BOBs live and does not require the technical skills of managing BOBs in cages. Watts started selling BOBs 10 years ago, and his business has steadily grown. In 2017 he had 700,000 BOBs for sale, although only around a third were female. He expects similar numbers for 2018 because the weather in 2017 was not great for BOB reproduction, but as his pool of BOBs increases, so does the potential for growth.

Compared with this method, Wardell's model can potentially ramp up the number of bees quickly. He started the 2016 season with 80,000 female bees and ended it with 400,000. After a disappointing 2017, he hopes to hit the mark of a million females in 2018. He could build 20 more acres of cages, put 100,000 females into them rather than into the orchards and, theoretically, within two years, be producing two million females annually.

Wardell's bees are not currently for sale to the public, but

JAY DUNN (1–4)

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THOUSANDS of blue orchard bee nest blocks, at different stages of metamorphosis (*1*), are stored in a temperature-controlled warehouse during winter (*2*). Colors denote the stage. Workers pull cocoons from nests (*3*), which are later warmed when it is time for the maturing bees to wake up and fly (*4*).

demand for BOBs among growers of early-blooming fruit is increasing. Watts says that when he started raising BOBs a decade ago, "we were begging people to do 10 acres." Now he has a waiting list, even though his BOBs are more expensive than honeybees. All the growers that bought bees in 2017 have signed up for them in 2018.

Theresa Pitts-Singer, who for years has studied BOBs at the USDA's Utah bee lab, thinks the bees are finally close to becoming a managed pollinator, reaching a "tipping point" she never thought they would reach. She is convinced because BOBs are increasingly available and growers want them, even though they are not cheap. She says that for a long time only one orchard pollination model was dependable: renting honeybees. Now more people seem to accept that other models might work—from bringing more wild bees onto farms to alternatives such as BOBs.

Although the researchers working with BOBs still have a long to-do list, they have a sense of momentum. They are developing grower-friendly management plans for a variety of orchard crops. More people are selling the bees, too, mostly using some version of wild trapping where the seller works to build the number of bees where they are gathered, a kind of bee farming. Wardell thinks that for BOBs to go mainstream, growers will need to change their pest-management practices, and Watts sees glimmers of hope in that direction. He puts it down to the power of ownership. When someone owns rather than rents bees, Watts says, "they rethink how they spray." Every bee saved means more pollinating power this year and less money spent the next.

Down in the Central Valley, Wardell recognizes the value of every bee, and in February 2018 his BOBs were scheduled to finally begin the job they had been bred for. But the long-term impact of Wardell's efforts may not be from his breakthroughs in the science of mass-producing bees. Instead it may be from something more subtle. Bill Kemp recently retired from the USDA after working with BOBs and other pollinators for decades. He says that when a large organization like Wonderful takes the risk to develop something, "it gets people's attention, and they're going to be more inclined to take the risk themselves," even if on a much smaller scale. "Don't underestimate the importance of the symbolic," he says. SA

This story was produced in collaboration with the Food & Environment Reporting Network, a nonprofit news organization.

MORE TO EXPLORE

Wildflower Plantings Do Not Compete with Neighboring Almond Orchards for Pollinator Visits. Ola Lundin et al. in *Environmental Entomology,* Vol. 46, No. 3, pages 559–564; June 1, 2017.

Bee Culture, the magazine of American beekeeping: **www.beeculture.com**

Bee Informed Partnership: **https://beeinformed.org**

FROM OUR ARCHIVES

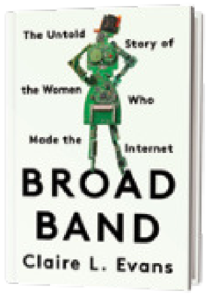
Saving the Honeybee. Diana Cox-Foster and Dennis vanEngelsdorp; April 2009.

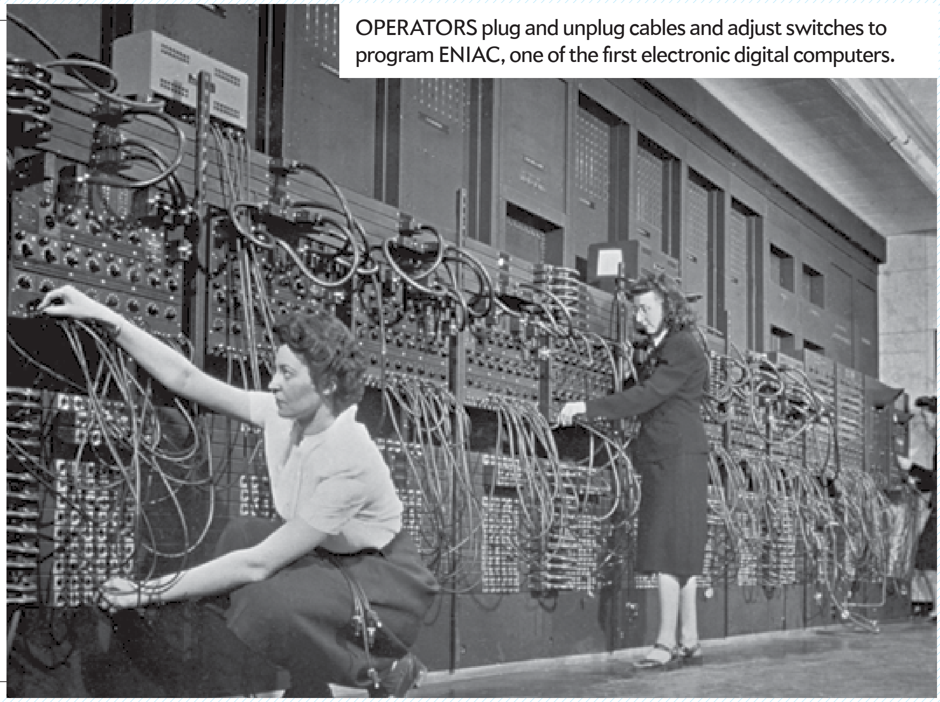
scientificamerican.com/magazine/sa

By Andrea Gawrylewski

Broad Band:
The Untold Story of the Women Who Made the Internet

by Claire L. Evans. Portfolio, 2018 ($27)



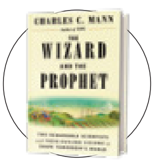


OPERATORS plug and unplug cables and adjust switches to program ENIAC, one of the first electronic digital computers.

In the earliest days of computing, rooms of women performed manual calculations for research projects run by the national defense agencies and the precursor to NASA. Though often marginalized and outnumbered by men, women stayed in the burgeoning field of computing long after their manual number crunching was replaced by lightning-fast machines connected by global information networks. In this inspiring tale, writer Evans chronicles the contributions of some of the many women who aided the rise of the modern Internet. Memorable characters include Elizabeth "Jake" Feinler, an information scientist who helped researchers navigate the Arpanet—a forerunner to the Internet—and Stacy Horn, who started one of the first social networks, Echo. As Evans puts it, women contributed to every stage in the development of computing technology: "We're not ancillary; we're central, often hiding in plain sight."

The Wizard and the Prophet: Two Remarkable Scientists and Their Dueling Visions to Shape Tomorrow's World

by Charles C. Mann. Knopf, 2018 ($28.95)



The human population is hurtling toward 10 billion—some experts think we'll nearly hit that mark by 2050. How will the earth feed, house and otherwise support such a hoard? Environmental thinkers usually fall into one of two camps: those who prioritize conservation and curbing consumption, and those who trust innovation to solve our problems. Writer Mann meticulously chronicles the lives and thought of the founders of these two philosophies. One is William Vogt, who advocated the way of caution and conservation; the other is Norman Borlaug, whose research ushered in the green revolution and who thought technology would find a way to save us.

A Lab of One's Own: Science and Suffrage in the First World War

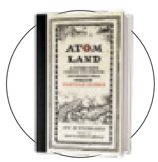
by Patricia Fara. Oxford University Press, 2018 ($24.95)

In World War I many women in the U.K. replaced their aprons with chemical suits and stepped into previously male-only domains of science, where they led war research efforts. Science historian Fara illustrates the lives of many of these forgotten women. Although the era marked a major step forward for women scientists, many worked for minuscule wages in an environment of blatant discrimination. Some were belittled as "opportunists" and forced to turn over their jobs to returning male soldiers. In the nearly 100 years since, women have come a long way, Fara writes, but the glass ceilings remain solid and the pipelines leaky.

—Yasemin Saplakoglu

Atom Land: A Guided Tour through the Strange (and Impossibly Small) World of Particle Physics

by Jon Butterworth. The Experiment, 2018 ($19.95)



Butterworth, a physicist at CERN's Large Hadron Collider near Geneva, takes readers on an amusing journey through the obscure world of particle physics. Using a metaphorical map as his guide and an imaginary boat as his vessel, he sets sail through subatomic waters. The first stop is "Atom Land," where Butterworth explains how electrons, protons and neutrons come together to build up everything we know. As the journey unfolds, we learn about lesser known particles—quarks, bosons and hadrons. We grapple with chameleon particles, supersymmetry and dark matter. Thankfully, our ship is stocked with tools such as mathematical equations and a "laser light" that illuminates the murkiest of concepts. *—Y.S.*

GETTY IMAGES

Michael Shermer is publisher of *Skeptic* magazine (www.skeptic.com) and a Presidential Fellow at Chapman University. His new book is *Heavens on Earth* (Henry Holt, 2018). Follow him on Twitter @michaelshermer

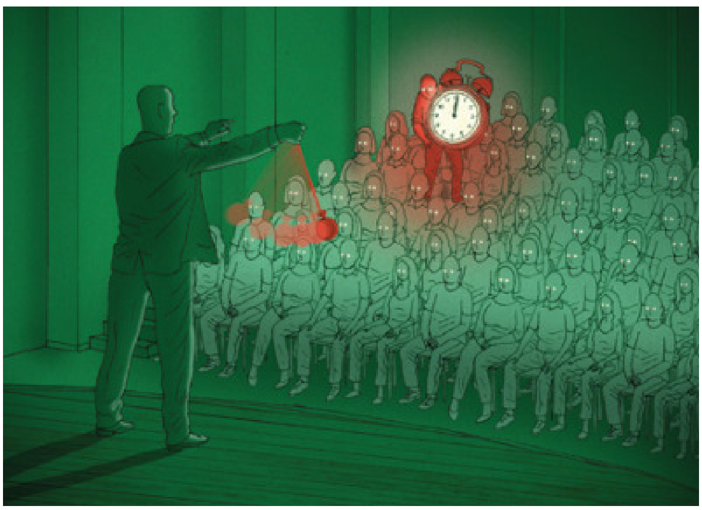
Factiness

Are we living in a post-truth world?

By Michael Shermer

In 2005 the American Dialect Society's word of the year was "truthiness," popularized by Stephen Colbert on his news show satire *The Colbert Report,* meaning "the truth we want to exist." In 2016 the Oxford Dictionaries nominated as its word of the year "post-truth," characterizing it as "relating to or denoting circumstances in which objective facts are less influential in shaping public opinion than appeals to emotion and personal belief." In 2017 "fake news" increased in usage by 365 percent, earning the top spot on the "word of the year shortlist" of the *Collins English Dictionary,* which defined it as "false, often sensational, information disseminated under the guise of news reporting."

Are we living in a post-truth world of truthiness, fake news and alternative facts? Has all the progress we have made since the scientific revolution in understanding the world and ourselves been obliterated by a fusillade of social media postings and tweets? No. As Harvard University psychologist Steven Pinker observes in his resplendent new book *Enlightenment Now: The Case for Reason,* *Science, Humanism, and Progress* (Viking, 2018), "mendacity, truth-shading, conspiracy theories, extraordinary popular delusions, and the madness of crowds are as old as our species, but so is the conviction that some ideas are right and others are wrong."



Even as pundits pronounced the end of veracity and politicians played loose with the truth, the competitive marketplace of ideas stepped up with a new tool of the Internet age: real-time fact-checking. As politicos spin-doctored reality in speeches, fact-checkers at Snopes.com, FactCheck.org and OpenSecrets.org rated them on their verisimilitude, with PolitiFact.com waggishly ranking statements as True, Mostly True, Half True, Mostly False, False, and Pants on Fire. Political fact-checking has even become clickbait (runner-up for the Oxford Dictionaries' 2014 word of the year), as PolitiFact's editor Angie Drobnic Holan explained in a 2015 article: "Journalists regularly tell me their media organizations have started highlighting fact-checking in their reporting because so many people click on fact-checking stories after a debate or high-profile news event."

Far from lurching backward, Pinker notes, today's fact-checking ethic "would have served us well in earlier decades when false rumors regularly set off pogroms, riots, lynchings, and wars (including the Spanish-American War in 1898, the escalation of the Vietnam War in 1964, the Iraq invasion of 2003, and many others)." And contrary to our medieval ancestors, he says, "few influential people today believe in werewolves, unicorns, witches, alchemy, astrology, bloodletting, miasmas, animal sacrifice, the divine right of kings, or supernatural omens in rainbows and eclipses."

Ours is called the Age of Science for a reason, and that reason is reason itself, which in recent decades has come under fire by cognitive psychologists and behavioral economists who assert that humans are irrational by nature and by postmodernists who aver that reason is a hegemonic weapon of patriarchal oppression. Balderdash! Call it "factiness," the quality of seeming to be factual when it is not. All such declarations are self-refuting, inasmuch as "if humans were incapable of rationality, we could never have discovered the ways in which they were irrational, because we would have no benchmark of rationality against which to assess human judgment, and no way to carry out the assessment," Pinker explains. "The human brain is *capable* of reason, given the right circumstances; the problem is to identify those circumstances and put them more firmly in place."

Despite the backfire effect, in which people double down on their core beliefs when confronted with contrary facts to reduce cognitive dissonance, an "affective tipping point" may be reached when the counterevidence is overwhelming and especially when the contrary belief becomes accepted by others in one's tribe. This process is helped along by "debiasing" programs in which people are introduced to the numerous cognitive biases that plague our species, such as the confirmation bias and the availability heuristic, and the many ways not to argue: appeals to authority, circular reasoning, ad hominem and especially ad Hitlerem. Teaching students to think critically about issues by having them discuss and debate all sides, especially articulating their own and another's position is essential, as is asking, "What would it take for you to change your mind?" This is an effective thinking tool employed by Portland State University philosopher Peter Boghossian.

"However long it takes," Pinker concludes, "we must not let the existence of cognitive and emotional biases or the spasms of irrationality in the political arena discourage us from the Enlightenment ideal of relentlessly pursuing reason and truth." That's a fact.

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Illustration by Izhar Cohen

Steve Mirsky has been writing the Anti Gravity column since a typical tectonic plate was about 36 inches from its current location. He also hosts the *Scientific American* podcast Science Talk.

A Staggering Discovery

Pride and falls have a complex relationship

By Steve Mirsky

Way back in 1999, when we, by definition, partied as per Prince's instructions, I wrote about a study concerning the advantages to humanity if we could get smaller. Not down to the five inches in height depicted in the 2017 movie *Downsizing* but enough to be noticeable. We would need less food, decrease our waste production and maybe even live longer. Another advantage, according to that old study: "When a 20% taller person trips, he or she hits the ground with 210% more kinetic energy than a shorter person."

I then noted that the calculation was the first I'd seen "for exactly how much harder they fall the bigger they come." But why did that taller person trip in the first place? According to another well-worn adage, "pride goeth before a fall." So was the stumblebum done in by self-regard?

Finally, we can address that question—at least among older British people—thanks to a new study entitled "Does Pride Really Come Before a Fall? Longitudinal Analysis of Older English Adults." The work appears in the famously flip Christmas issue of the *BMJ,* which always features merry research. (It downsized its name from the *British Medical Journal* in 1988, thereby passing on the costs of ink to other publications that need to explain what the *BMJ* is.)

The researchers looked at data for people at least 60 years old from the English Longitudinal Study of Ageing (ELSA). At one point in this long-term investigation, subjects were asked, "During the past 30 days, to what degree did you feel proud?" The choices were: "not at all," "a little," "moderately," "quite a bit" and "very much." The *BMJ* researchers collapsed those responses to low (for the first two), high (for the last two) and moderate (for "moderately," which is a good thing). ELSA participants had also been asked if they'd fallen down recently.

Data sets in hand, the game was afoot. The researchers crunched the numbers and found convincing evidence that pride doth not appear to goeth before a fall at all. "Unsurprisingly," they wrote, "this is the first study to investigate temporal associations between pride and subsequent reported falls in a large sample of English older adults. Contrary to the proverb, our findings suggest that pride may actually be protective against falls rather than being a contributing factor."

In fact, after controlling for confounding factors, the team found that "the odds of having had a reported fall … was 19% lower for people with high levels of pride compared with those who had low levels."

Clearly, these rigorous scientific findings raise a vital question. As the researchers themselves ask, "Do these findings undermine the validity of biblical wisdom in its application to contemporary health outcomes?" But, they point out, "the keen biblical scholar will have noted that 'pride comes before a fall' is, in fact, an inaccurate paraphrase of Proverbs chapter 16 verse 18, which reads 'pride goes before destruction, and a haughty spirit before a fall,'" and that "the saying 'pride comes before a fall' more likely refers to metaphorical moral or ethical falls, not literal ones."

Rendering unto Caesar what is Caesar's, how then to explain a significant decrease in fall risk with feeling proud? The authors of the *BMJ* paper give it a go: "In the case of pride, higher levels are likely to be reflective of, or a driver of, higher levels of general subjective wellbeing, which has been shown to have close associations with physical health. Physical manifestations of pride may also make people with high levels of pride less likely to fall—for example, having a more upright and confident posture, walking with the head raised high giving better sight of oncoming obstacles, and walking with a purposeful gait."

Of course, these results apply only to older English people. Here in the U.S., we have the fascinating case of the now 71-year-old orange-hued man who tweeted on December 3, 2015, "I have instructed my long-time doctor to issue, within two weeks, a full medical report—it will show perfection." Look out below. SA

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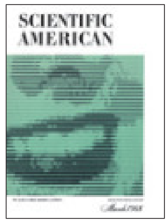
Illustration by Matt Collins

50, 100 & 150 YEARS AGO

INNOVATION AND DISCOVERY AS CHRONICLED IN *SCIENTIFIC AMERICAN*

Compiled by Daniel C. Schlenoff

MARCH



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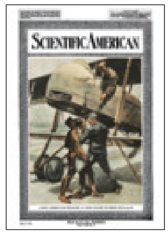
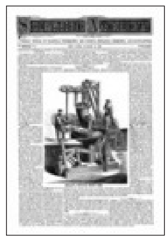


1918


1868

1968 Hayflick Limit

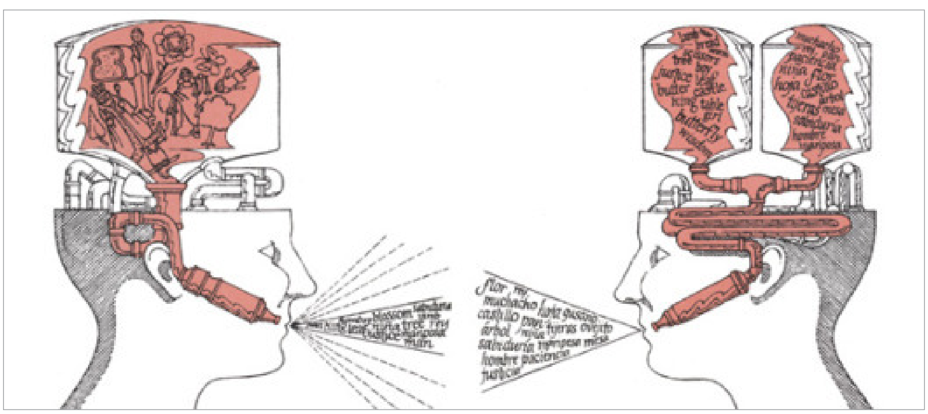
"Could man's life-span be extended, or is there an inescapable aging mechanism that restricts human longevity to the present apparent limit? Until recently few biologists ventured to attempt to explore the basic processes of aging; obviously the subject does not easily lend itself to detailed study. No doubt many mechanisms are involved in the aging of the body. In our own laboratory at the Wistar Institute we have addressed ourselves to one question: the limitation on cell division. Our studies have focused particularly on the structural cells called fibroblasts, which produce collagen and fibrin. These cells, like certain other 'blast' cells, go on dividing in the adult body. We set out to determine whether human fibroblasts in a cell culture could divide indefinitely or had only a finite capacity for doing so.—Leonard Hayflick"

Bilingual Convergence

"By presenting a bilingual subject with information in one language and then testing him in the other, the investigator should be able to learn much about the mental operations involved in the acquisition, storage and retrieval of the information. Two hypotheses about the way a bilingual person handles information are represented by two arrangements of tanks. One hypothesis (*left in illustration*) is that all his information is stored centrally, or in one tank, and that he has access to it equally with both languages, which are represented by the various taps. The other (*right*) is that his information is stored in linguistically associated ways, or in separate tanks. Experiments by the author indicated that the actual situation of a bilingual person combines parts of both hypotheses."

1918 Germany's Next War

"A book written by Lieut. General Baron von Freytag-Loringhoven bears the title *Deductions from the World War*. The General is Deputy Chief of the General Staff. Although the General does not, of course, put it down in bald English that Germany has failed in the present war, it is impossible to read this work without realizing that the Grand General Staff understands that the great stake for which they played is lost—at least for the present. This von Freytag-Loringhoven gives us to understand that Germany would make this war with all its vast experience, the stepping-stone for another attempt which shall surely win out."



SCIENTIFIC AMERICAN, VOL. 218, NO. 3; MARCH 1968; CARTOON BY CHAS. SLACKMAN

1968: Information storage "tanks" in the bilingual brain can be accessed either equally in both languages or associated with different languages.

Malarial Comeback

"Malaria was once common in certain parts of England, but as a result of drainage and the use of quinine, it was completely stamped out, notwithstanding the fact that anopheline mosquitoes remain in the country. The parasitic cycle was broken, and the insect was no longer infected. Now comes the report of a recrudescence of indigenous malaria in England. According to a circular issued by the Local Government Board, many men have contracted the disease while fighting on the eastern war fronts, and have brought it home with them; thus they serve as foci of infection for the civilian population."

1868 Cholera Subdued

"There now seems good reason to believe that epidemic cholera has been conquered by the power of intelligence. Among the many substances that are produced when bituminous coal is subjected to destructive distillation is a compound which has acquired the name of carbolic gas. It is this substance which seems to have given man control over the last and most terrible pestilences that have desolated the world. During the summer and fall of 1866 the cholera several times secured a foothold in this city [New York], and every time it was stamped out by the Board of Health. Dr. Harris and other members of the Board regard carbolic acid as the most efficient agent which they employed."

The Ugly American

"A correspondent recently returned from the East says: 'In Turkey, in Asia, the only mode of measuring distances is by the walking gait of a horse, and the traveler is told, when he inquires the distance to a given village or city, that it is so many caravan *days* or *hours*, which of course is not uniformly the same. This to a stranger is a great annoyance.'"

Text and Graphic by Katie Peek

The Case for Daylight Saving Time

Research shows that the benefits may outweigh the drawbacks

The Shift
The U.S. and Canada operate on daylight saving time from the second Sunday in March to the first Sunday in November. Sunrise and sunset times **A** jump by an hour; sunrise shifts to later in the morning (*top curves*) and sunset to later at night (*bottom curves*). As a result, the sun rises at a more consistent time throughout the year and sets at a wider range of times. Evidence is mixed about whether changing the clocks is worthwhile **B**.

A Sunrise and Sunset in 2018

Miami
This far south, sunrise and sunset vary by just an hour across the year. DST or not, the times align well with a 9-to-5 schedule.

Seattle
In midlatitude cities, DST keeps the summer sun from rising too early; standard time keeps the winter sun from rising too late.

Fairbanks, Alaska
Daylight varies dramatically for places closer to the earth's poles. Even with DST, the summer sun can rise at 3 A.M. and set after midnight.

B Pros and Cons

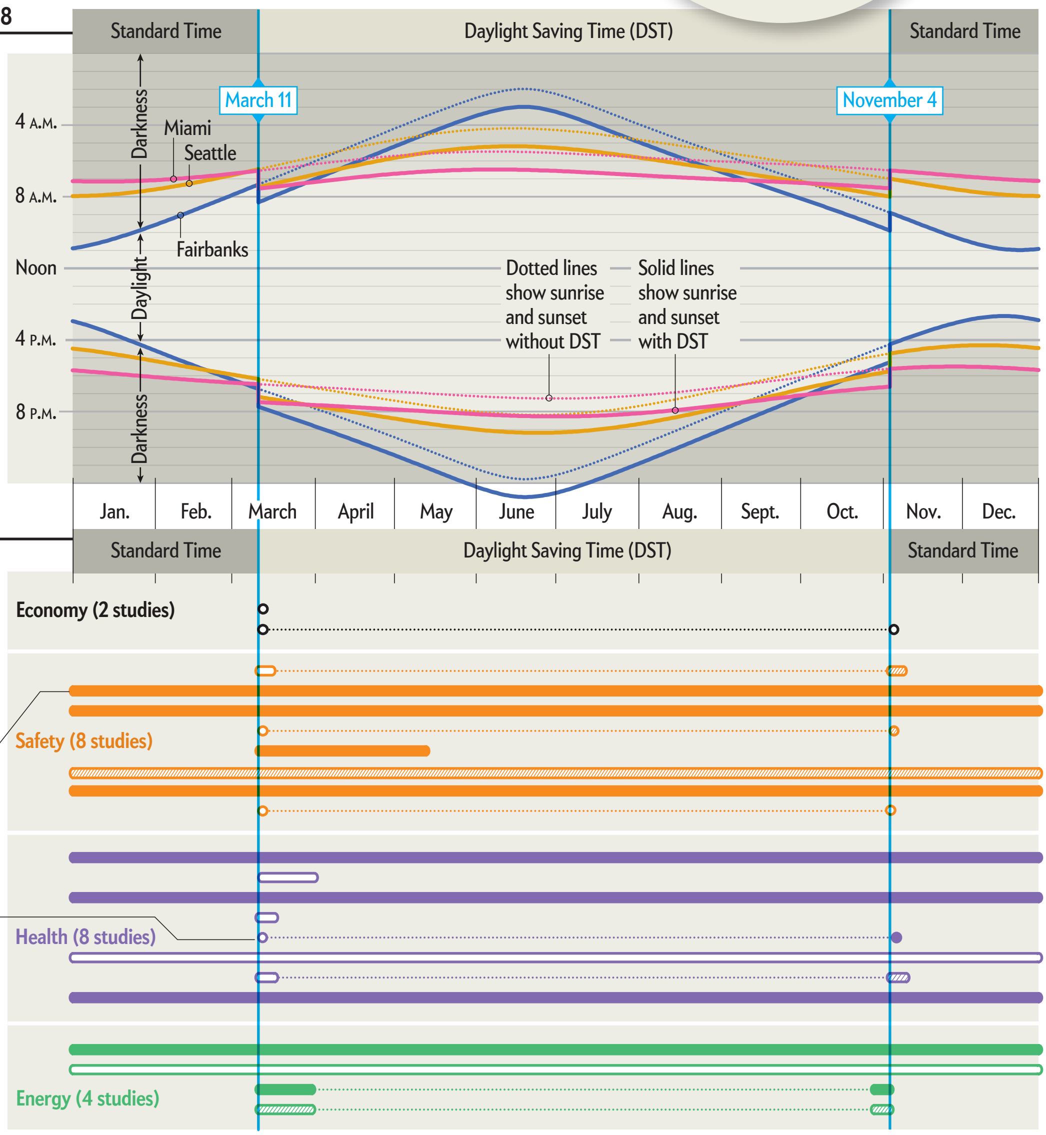
Twenty-two research reports on DST since 2000 are shown across the time periods they studied. Negative effects of DST tend to occur near the time-change dates; benefits often stretch over the year.

- ● Study supports DST
- ○ Study opposes DST
- ⊘ Study has mixed results

Crime rates drop
Lighter evenings lead to fewer robberies, a 2015 study found.

Heart attacks up … and down
One study found heart attacks increase after the spring shift but drop after the fall change.

Energy savings neutral
Northern states save energy during DST; southern states save less (likely from the use of air-conditioning).



A century ago, in 1918, the U.S. started the collective clock-changing ritual known as daylight saving time, or DST. Today more than 70 countries observe the practice, although how it is implemented has varied over the years. In general, the one-hour shift prevents sunrise from happening too early and allows sundown to go later, when compared with a typical work day of 9 A.M. to 5 P.M. Debates about the practice have raged since it began. In recent years the U.S. government's stated goal for DST is to save energy by adding natural light to evenings. Several new studies have pointed to some liabilities, such as higher rates of heart attacks and traffic accidents after citizens set their clocks forward each spring. "The shift to DST has some drawbacks," but many ill effects last just a few days, says David Prerau, who wrote a book on the practice. "Balance that against eight months of later sunsets."

SOURCE: ASTRONOMICAL APPLICATIONS DEPARTMENT OF THE U.S. NAVAL OBSERVATORY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